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Computational Science and Its Applications – ICCSA 2023 Workshops

Athens, Greece, July 3–6, 2023
Proceedings, Part III





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Editors

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Preface

These 9 volumes (LNCS volumes 14104–14112) consist of the peer-reviewed papers from the 2023 International Conference on Computational Science and Its Applications (ICCSA 2023) which took place during July 3–6, 2023. The peer-reviewed papers of the main conference tracks were published in a separate set consisting of two volumes (LNCS 13956–13957).

The conference was finally held in person after the difficult period of the Covid-19 pandemic in the wonderful city of Athens, in the cosy facilities of the National Technical University. Our experience during the pandemic period allowed us to enable virtual participation also this year for those who were unable to attend the event, due to logistical, political and economic problems, by adopting a technological infrastructure based on open source software (jitsi + riot), and a commercial cloud infrastructure.

ICCSA 2023 was another successful event in the International Conference on Computational Science and Its Applications (ICCSA) series, previously held as a hybrid event (with one third of registered authors attending in person) in Malaga, Spain (2022), Cagliari, Italy (hybrid with few participants in person in 2021 and completely online in 2020), whilst earlier editions took place in Saint Petersburg, Russia (2019), Melbourne, Australia (2018), Trieste, Italy (2017), Beijing, China (2016), Banff, Canada (2015), Guimaraes, Portugal (2014), Ho Chi Minh City, Vietnam (2013), Salvador, Brazil (2012), Santander, Spain (2011), Fukuoka, Japan (2010), Suwon, South Korea (2009), Perugia, Italy (2008), Kuala Lumpur, Malaysia (2007), Glasgow, UK (2006), Singapore (2005), Assisi, Italy (2004), Montreal, Canada (2003), and (as ICCS) Amsterdam, The Netherlands (2002) and San Francisco, USA (2001).

Computational Science is the main pillar of most of the present research, industrial and commercial applications, and plays a unique role in exploiting ICT innovative technologies, and the ICCSA series have been providing a venue to researchers and industry practitioners to discuss new ideas, to share complex problems and their solutions, and to shape new trends in Computational Science. As the conference mirrors society from a scientific point of view, this year's undoubtedly dominant theme was the machine learning and artificial intelligence and their applications in the most diverse economic and industrial fields.

The ICCSA 2023 conference is structured in 6 general tracks covering the fields of computational science and its applications: Computational Methods, Algorithms and Scientific Applications – High Performance Computing and Networks – Geometric Modeling, Graphics and Visualization – Advanced and Emerging Applications – Information Systems and Technologies – Urban and Regional Planning. In addition, the conference consisted of 61 workshops, focusing on very topical issues of importance to science, technology and society: from new mathematical approaches for solving complex computational systems, to information and knowledge in the Internet of Things, new statistical and optimization methods, several Artificial Intelligence approaches, sustainability issues, smart cities and related technologies.

In the workshop proceedings we accepted 350 full papers, 29 short papers and 2 PHD Showcase papers. In the main conference proceedings we accepted 67 full papers, 13 short papers and 6 PHD Showcase papers from 283 submissions to the General Tracks of the conference (acceptance rate 30%). We would like to express our appreciation to the workshops chairs and co-chairs for their hard work and dedication.

The success of the ICCSA conference series in general, and of ICCSA 2023 in particular, vitally depends on the support of many people: authors, presenters, participants, keynote speakers, workshop chairs, session chairs, organizing committee members, student volunteers, Program Committee members, Advisory Committee members, International Liaison chairs, reviewers and others in various roles. We take this opportunity to wholehartedly thank them all.

We also wish to thank our publisher, Springer, for their acceptance to publish the proceedings, for sponsoring part of the best papers awards and for their kind assistance and cooperation during the editing process.

We cordially invite you to visit the ICCSA website https://iccsa.org where you can find all the relevant information about this interesting and exciting event.

July 2023

Osvaldo Gervasi
Beniamino Murgante
Chiara Garau

Welcome Message from Organizers

After the 2021 ICCSA in Cagliari, Italy and the 2022 ICCSA in Malaga, Spain, ICCSA continued its successful scientific endeavours in 2023, hosted again in the Mediterranean neighbourhood. This time, ICCSA 2023 moved a bit more to the east of the Mediterranean Region and was held in the metropolitan city of Athens, the capital of Greece and a vibrant urban environment endowed with a prominent cultural heritage that dates back to the ancient years. As a matter of fact, Athens is one of the oldest cities in the world, and the cradle of democracy. The city has a history of over 3,000 years and, according to the myth, it took its name from Athena, the Goddess of Wisdom and daughter of Zeus.

ICCSA 2023 took place in a secure environment, relieved from the immense stress of the COVID-19 pandemic. This gave us the chance to have a safe and vivid, in-person participation which, combined with the very active engagement of the ICCSA 2023 scientific community, set the ground for highly motivating discussions and interactions as to the latest developments of computer science and its applications in the real world for improving quality of life.

The National Technical University of Athens (NTUA), one of the most prestigious Greek academic institutions, had the honour of hosting ICCSA 2023. The Local Organizing Committee really feels the burden and responsibility of such a demanding task; and puts in all the necessary energy in order to meet participants' expectations and establish a friendly, creative and inspiring, scientific and social/cultural environment that allows for new ideas and perspectives to flourish.

Since all ICCSA participants, either informatics-oriented or application-driven, realize the tremendous steps and evolution of computer science during the last few decades and the huge potential these offer to cope with the enormous challenges of humanity in a globalized, 'wired' and highly competitive world, the expectations from ICCSA 2023 were set high in order for a successful matching between computer science progress and communities' aspirations to be attained, i.e., a progress that serves real, place- and people-based needs and can pave the way towards a visionary, smart, sustainable, resilient and inclusive future for both the current and the next generation.

On behalf of the Local Organizing Committee, I would like to sincerely thank all of you who have contributed to ICCSA 2023 and I cordially welcome you to my 'home', NTUA.

On behalf of the Local Organizing Committee.

Anastasia Stratigea

Organization

ICCSA 2023 was organized by the National Technical University of Athens (Greece), the University of the Aegean (Greece), the University of Perugia (Italy), the University of Basilicata (Italy), Monash University (Australia), Kyushu Sangyo University (Japan), the University of Minho (Portugal). The conference was supported by two NTUA Schools, namely the School of Rural, Surveying and Geoinformatics Engineering and the School of Electrical and Computer Engineering.

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Plenary Lectures

A Multiscale Planning Concept for Sustainable Metropolitan Development

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Urban sprawl has often been pointed out as having an important negative impact on environment and climate. Residential zones have grown up in what were initially rural areas, located far from employment areas and often lacking shopping opportunities, public services and public transportation. Hence urban sprawl increased car-traffic flows, generating pollution and increasing energy consumption. New road axes consume considerable space and weaken biodiversity by reducing and cutting natural areas. A return to "compact cities" or "dense cities" has often been contemplated as the most efficient way to limit urban sprawl. However, the real impact of density on car use is less clear-cut (Daneshpour and Shakibamanesh 2011). Let us emphasize that moreover climate change will increase the risk of heat islands on an intra-urban scale. This prompts a more nuanced reflection on how urban fabrics should be structured.

Moreover, urban planning cannot ignore social demand. Lower land prices in rural areas, often put forward by economists, is not the only reason of urban sprawl. The quality of the residential environment comes into play, too, through features like noise, pollution, landscape quality, density etc. Schwanen et al. (2004) observe for the Netherlands that households preferring a quiet residential environment and individual housing with a garden will not accept densification, which might even lead them to move to lower-density rural areas even farther away from jobs and shopping amenities. Many scholars emphasize the importance of green amenities for residential environments and report the importance of easy access to leisure areas (Guo and Bhat 2002). Vegetation in the residential environment has an important impact on health and well-being (Lafortezza et al. 2009).

We present here the Fractalopolis concept which we developed in the frame of several research projects and which aims reconciling environmental and social issues (Bonin et al., 2020; Frankhauser 2021; Frankhauser et al. 2018). This concept introduces a multiscale approach based on multifractal geometry for conceiving spatial development for metropolitan areas. For taking into account social demand we refer to the fundamental work of Max-Neef et al. (1991) based on Maslow's work about basic human needs. He introduces the concept of satisfiers assigned to meet the basic needs of "Subsistence, Protection, Affection, Understanding, Participation, Idleness, Creation, Identity and Freedom". Satisfiers thus become the link between the needs of everyone and society

and may depend on the cultural context. We consider their importance, their location and their accessibility and we rank the needs according to their importance for individuals or households. In order to enjoy a good quality of life and to shorten trips and to reduce automobile use, it seems important for satisfiers of daily needs to be easily accessible. Hence, we consider the purchase rate when reflecting on the implementation of shops which is reminiscent of central place theory.

The second important feature is taking care of environment and biodiversity by avoiding fragmentation of green space (Ekren and Arslan 2022) which must benefit, moreover, of a good accessibility, as pointed out. These areas must, too, ply the role of cooling areas ensuring ventilation of urbanized areas (Kuttler et al. 1998).

For integrating these different objectives, we propose a concept for developing spatial configurations of metropolitan areas designed which is based on multifractal geometry. It allows combining different issues across a large range of scales in a coherent way. These issues include:

- providing easy access to a large array of amenities to meet social demand;
- promoting the use of public transportation and soft modes instead of automobile use;
- preserving biodiversity and improving the local climate.

The concept distinguishes development zones localized in the vicinity of a nested and hierarchized system of public transport axes. The highest ranked center offers all types of amenities, whereas lower ranked centers lack the highest ranked amenities. The lowest ranked centers just offer the amenities for daily needs. A coding system allows distinguishing the centers according to their rank.

Each subset of central places is in some sense autonomous, since they are not linked by transportation axes to subcenters of the same order. This allows to preserve a linked system of green corridors penetrating the development zones across scales avoiding the fragmentation of green areas and ensuring a good accessibility to recreational areas.

The spatial model is completed by a population distribution model which globally follows the same hierarchical logic. However, we weakened the strong fractal order what allows to conceive a more or less polycentric spatial system.

We can adapt the theoretical concept easily to real world situation without changing the underlying multiscale logic. A decision support system has been developed allowing to simulate development scenarios and to evaluate them. The evaluation procedure is based on fuzzy evaluation of distance acceptance for accessing to the different types of amenities according to the ranking of needs. We used for evaluation data issued from a great set of French planning documents like Master plans. We show an example how the software package can be used concretely.

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Graph Drawing and Network Visualization – An Overview – (Keynote Speech)

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Abstract. Graph Drawing and Network visualization supports the exploration, analysis, and communication of relational data arising in a variety of application domains: from bioinformatics to software engineering, from social media to cyber-security, from data bases to powergrid systems. Aim of this keynote speech is to introduce this thriving research area, highlighting some of its basic approaches and pointing to some promising research directions.

1 Introduction

Graph Drawing and Network Visualization is at the intersection of different disciplines and it combines topics that traditionally belong to theoretical computer science with methods and approaches that characterize more applied disciplines. Namely, it can be related to Graph Algorithms, Geometric Graph Theory and Geometric computing, Combinatorial Optimization, Experimental Analysis, User Studies, System Design and Development, and Human Computer Interaction. This combination of theory and practice is well reflected in the flagship conference of the area, the *International Symposium on Graph Drawing and Network Visualization*, that has two tracks, one focusing on combinatorial and algorithmic aspects and the other on the design of network visualization systems and interfaces. The conference is now at its 31st edition; a full list of the symposia and their proceedings, published by Springer in the LNCS series can be found at the URL: http://www.graphdrawing.org/.

Aim of this short paper is to outline the content of my Keynote Speech at ICCSA 2023, which will be referred to as the "Talk" in the rest of the paper. The talk will introduce the field of Graph Drawing and Network Visualization to a broad audience, with the goal to not only present some key methodological and technological aspects, but also point to some unexplored or partially explored research directions. The rest of this short paper briefly outlines the content of the talk and provides some references that can be a starting point for researchers interested in working on Graph Drawing and Network Visualization.

2 Why Visualize Networks?

Back in 1973 the famous statistician Francis Anscombe, gave a convincing example of why visualization is fundamental component of data analysis. The example is known as the *Anscombe's quartet* [3] and it consists of four sets of 11 points each that are almost identical in terms of the basic statistic properties of their x– and y– coordinates. Namely the mean values and the variance of x and y are exactly the same in the four sets, while the correlation of x and y and the linear regression are the same up to the second decimal. In spite of this statistical similarity, the data look very different when displayed in the Euclidean plane which leads to the conclusion that they correspond to significantly different phenomena. Figure 1 reports the four sets of Anscombe's quartet. After fifty years, with the arrival of AI-based technologies and the need of explaining and interpreting machine-driven suggestions before making strategic decision, the lesson of Anscombe's quartet has not just kept but even increased its relevance.

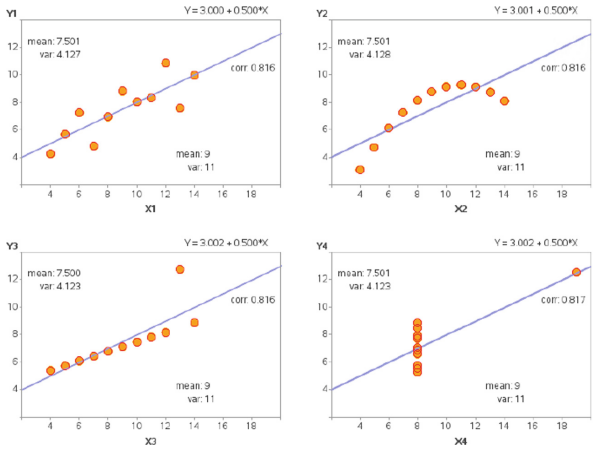

Fig. 1. The four point sets in Anscombe's quartet [3]; the figure also reports statistical values of the x and y variables.

As a matter of fact, nowadays the need of visualization systems goes beyond the verification of the accuracy of some statistical analysis on a set of scattered data. Recent technological advances have generated torrents of data that area relational in nature and typically modeled as networks: the nodes of the networks store the features of the data and the edges of the networks describe the semantic relationships between the data features. Such networked data sets (whose algebraic underlying structure is a called graph in discrete mathematics) arise in a variety of application domains including, for example, Systems Biology, Social Network Analysis, Software Engineering, Networking, Data Bases, Homeland Security, and Business Intelligence. In these (and many other) contexts, systems that support the visual analysis of networks and graphs play a central role in critical decision making processes. These are human-in-the-loop processes where the

continuous interaction between humans (decision makers) and data mining or optimization algorithms (AI/ML components) supports the data exploration, the development of verifiable theories about the data, and the extraction of new knowledge that is used to make strategic choices. A seminal book by Keim et al. [33] schematically represents the human-in-the-loop approach to making sense of networked data sets as in Fig. 2. See also [46–49].

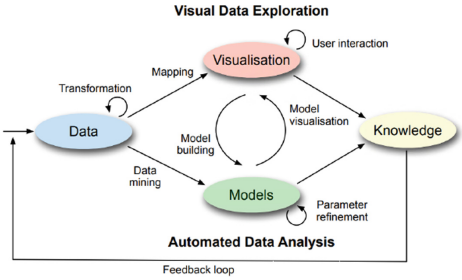

Fig. 2. Sense-making/knowledge generation loop. This conceptual interaction model between human analysts and network visualization system is at the basis of network visual analytics system design [33].

To make a concrete application example of the analysis of a network by interacting with its visualization, consider the problem of contrasting financial crimes such as money laundering or tax evasion. These crimes are based on relevant volumes of financial transactions to conceal the identity, the source, or the destination of illegally gained money. Also, the adopted patterns to pursue the illegal goals continuously change to conceal the crimes. Therefore, contrasting them requires special investigation units which must analyze very large and highly dynamic data sets and discover relationships between different subjects to untangle complex fraudulent plots. The investigative cycle begins with data collection and filtering; it is then followed by modeling the data as a social network (also called *financial activity network* in this context) to which different data mining and data analytic methods are applied, including graph pattern matching, social network analysis, machine learning, and information diffusion. By the network visualization system detectives can interactively explore the data, gain insight and make new hypotheses about possible criminal activities, verify the hypotheses by asking the system to provide more details about specific portions of the network, refine previous outputs, and eventually gain new knowledge. Figure 3 illustrates a small financial activity network where, by means of the interaction between an officer of the Italian Revenue Agency and the MALDIVE system described in [10] a fraudulent pattern has been identified. Precisely, the tax officer has encoded a risky relational scheme among taxpayers into a suspicious graph pattern; in response, the system has made a search in the taxpayer network and it has returned one such pattern. See, e.g., [9, 11, 14, 18, 38] for more papers and references about visual analytic applications to contrasting financial crimes.

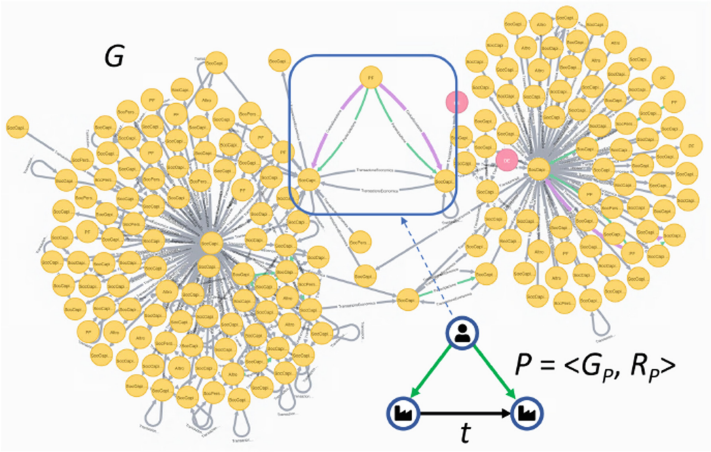

Fig. 3. A financial activity network from [10]. The pattern in the figure represents a SuppliesFromAssociated scheme, consisting of an economic transaction and two shareholding relationships.

3 Facets of Graph Drawing and Network Visualization

The Talk overviews some of the fundamental facets that characterize the research in Graph Drawing and Network Visualization. Namely:

- Graph drawing metaphors: Depending on the application context, different metaphors can be used to represent a relational data set modeled as a graph. The talk will briefly recall the matrix representation, the space filling representation, the contact representation, and the node-link representation which is, by far, the most commonly used (see, e.g., [43]).
- Interaction paradigms: Different interaction paradigms have different impacts on the sense-making process of the user about the visualized network. The Talk will go through the full-view, top-down, bottom-up, incremental, and narrative paradigms. Pros and cons will be highlighted for each approach, also by means of examples and applications. The discussion of the top-down interaction paradigm will also consider the hybrid visualization models (see, e.g., [2, 24, 26, 28, 39]) while the discussion about the incremental paradigm will focus on research about graph storyplans (see, e.g., [4, 6, 7]).
- Graph drawing algorithms: Three main algorithmic approaches will be reviewed, namely the force-directed, the layered), and the planarization-based approach; see, e.g., [5]. We shall also make some remarks about FPT algorithms for graph drawing (see, e.g., [8, 19, 20, 25, 27, 40, 53]) and about how the optimization challenges vary when it is assumed that the input has or does not have a fixed combinatorial embedding (see, e.g., [12, 13, 16, 17, 23]).
- Experimental analysis and user-studies: The Talk will mostly compare two models to define and experimentally validate those optimization goals that define a “readable”

network visualization, i.e. a visualization that in a given application context can easily convey the structure of a relational data set so to guarantee efficiency both in its visual exploration and in the elaboration of new knowledge. Special focus will be given to a set emerging optimization goals related to edge crossings that are currently investigated in the graph drawing and network visualization community unedr the name of "graph drawing beyond planarity" (see, e.g., [1, 15, 29, 35]).

The talk shall also point to some promising research directions, including: (i) Extend the body of papers devoted to user-studies that compare the impact of different graph drawing metaphors on the user perception. (ii) Extend the study of interaction paradigms to extended reality environments (see, e.g., [21, 30, 36, 37]); (iii) Engineer the FPT algorithms for graph drawing and experimentally compare their performances with exact or approximate solutions; and (iv) Develop new algorithmic fameworks in the context of graph drawing beyond planarity.

We conclude this short paper with pointers to publication venues and key references that can be browsed by researchers interested in the fascinating field of Graph Drawing and Network Visualization.

4 Pointers to Publication venues and Key References

A limited list of conferences where Graph Drawing and Network Visualization papers are regularly part of the program includes *IEEE VIS, EuroVis, SoCG, ISAAC, ACM-SIAM SODA, WADS,* and *WG*. Among the many journals where several Graph Drawing and Network Visualization papers have appeared during the last three decades we recall *IEEE Transactions on Visualization and Computer Graphs, SIAM Jounal of Computing, Computer Graphics Forum, Journal of Computer and System Sciences, Algorithmica, Journal of Graph Algorithms and Applications, Theoretical Computer Science, Information Sciences, Discrete and Computational Geometry, Computational Geometry: Theory and Applications, ACM Computing Surveys,* and *Computer Science Review*. A limited list of books, surveys, or papers that contain interesting algorithmic challenges on Graph Drawing and Network Visualization include [5, 15, 22, 29, 31–35, 41–45, 50–52].

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Understanding Non-Covalent Interactions in Biological Processes through QM/MM-EDA Dynamic Simulations

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Molecular dynamic simulations in biological environments such as proteins, DNA or lipids involves a large number of atoms, so classical models based on widely parametrized force fields are employed instead of more accurate quantum methods, whose high computational requirements preclude their application. The parametrization of appropriate force fields for classical molecular dynamics relies on the precise knowledge of the non-covalent inter and intramolecular interactions responsible for very important aspects, such as macromolecular arrangements, cell membrane permeation, ion solvation, etc. This implies, among other things, knowledge of the nature of the interaction, which may be governed by electrostatic, repulsion or dispersion forces. In order to know the balance between different forces, quantum calculations are frequently performed on simplified molecular models and the data obtained from these calculations are used to parametrize the force fields employed in classical simulations. These parameters are, among others, atomic charges, permanent electric dipole moments and atomic polarizabilities. However, it sometimes happens that the molecular models used for the quantum calculations are too simple and the results obtained can differ greatly from those of the extended system. As an alternative to classical and quantum methods, hybrid quantum/classical schemes (QM/MM) can be introduced, where the extended system is neither truncated nor simplified, but only the most important region is treated quantum mechanically.

In this presentation, molecular dynamic simulations and calculations with hybrid schemes are first introduced in a simple way for a broad and multidisciplinary audience. Then, a method developed in our group to investigate intermolecular interactions using hybrid quantum/classical schemes (QM/MM-EDA) is presented and some applications to the study of dynamic processes of ion solvation and membrane permeation are discussed [1–3]. Special attention is paid to the implementation details of the method in the EDA-NCI software [4].

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Computational Methods for Porous Geomaterials (CompPor 2023)

Simulation of Two-Phase Flow in Models with Micro-porous Material

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Abstract. The paper presents an original numerical algorithm to simulate coupled two-phase fluid flow in domains containing open pores and microporous material. To simulate the coupled flow we use the time-dependent Navier-Stokes-Brinkman equation. The transport of the phases is governed by the Cahn-Hilliard equation in the open pores and by the Buckley-Leverett equation in the porous material. We suggested a unified finite-difference approximation of the two transport equations, that satisfy the natural conjugation conditions. However, Cahn-Hilliard requires an additional boundary condition, that must be satisfied at the interface to ensure the wetting angle.

Keywords: Phase-field method · flow in porous media · finite-difference simulation

1 Introduction

Pore-scale numerical simulation of fluid flow is the main application of digital rock physics (DRP). DRP allows estimating effective physical properties of rocks by numerical experiments using the micro CT-images as the rock model [3,4]. Indeed, this method can be implemented to estimate almost any property of core samples including electrical resistivity [4,19], elastic parameters such as bulk modulus or the components of the stiffness tensor [4,18,32], attenuation coefficients of seismic waves [2] and other. However, the fluid flow simulation is the most widely used application, because its results may be applied to hydrocarbon exploration, greenhouse gas sequestration as well as chemical engineering. In particular, one phase flow simulation is used to estimate absolute permeability,

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open porosity, and tortuosity of the pore space of the samples [4,6]. Reactive transport simulations allow understanding the peculiarities of chemical fluid-solid interaction, which may be crucial for CO_2 sequestration or CO_2 sorption [1,23,27,28,30].

Two- and multi-phase flow simulation in a pore space with complex topology is a challenging task that requires accurate numerical treatment of the moving interface. There are several approaches to resolve this issue, including direct front-tracking methods [15], level-set method [14,29], and the phase-field method [7,20,34]. The first approach is hard to implement in 3D cases, especially in domains with complex topology. The second approach allows defining the interface implicitly as the zero level of the signed distance function. It allows for treating complex geometry of the computational domain. However, it suffers from a nonphysical change of the phase volume, which requires additional regularization [17,33]. Moreover, the approximation of the wetting angle condition is also a challenging task for the level-set method. In the phase field method, the diffused interface approach is applied; i.e., the interface between the phases is smoothed out over several grid cells. It makes the concentration function smooth enough to be treated by finite differences, finite volumes, or finite elements [20]. However, an additional fourth-order differential equation called the Cahn-Hilliard equation should be solved. Due to its simplicity and applicability to the domains of almost arbitrary complexity, this approach is getting a common tool in pore-scale fluid flow simulation.

However, commonly porous materials may contain several scales of pores; i.e., the big enough pores may be filled with the microporous material which is still capable to support multi-phase flow. If a single-phase flow is considered, the coupled flow may be simulated by either explicit domain decomposition with multi-physical approaches; or by the unified Navier-Stokes-Brinkman equation [5]. However, there is no unified approach to treat the phase transport in the open pores (where the Cahn-Hilliard equation is valid) and the microporous material (where the Buckley-Leverett equation is stated). Nowadays, the widely-used approach to simulate coupled two-phase transport is based on the volume of a fluid method as reported in [10] and [11], but no coupled transport simulated with the phase-field method with the unified formulation of the Cahn-Hilliard and Buckley-Leverett equation has been published. In this paper, we present such an approach and illustrate its applicability through a series of numerical simulations in fully 3D cases.

2 Statement of the Problem

We consider the model of the rock with pores that a filled with permeable microporous material as well as open pores. We assume that the fluid flow in the open pores is governed by the Navier-Stokes equation, whereas the flow in the microporous material satisfies the Darcy law. Under this statement, we need to simulate the coupled flow of the two-phase flow of incompressible fluids. Let us introduce the computational domain $\Omega = [0; L_1] \times [0, L_2] \times [0, L_3]$ corresponding

to a CT-scan of a core. The domain is composed of three non-overlapping (multi-connected) domains Ω_s is the solid impermeable rock matrix, Ω_p is the domain filled with permeable microporous material, and Ω_o is the domain corresponding to opened pores. We also need to introduce the boundaries and interfaces. The boundary of the first type denoted as Γ_b corresponds to the sides of the computational domain $x_2 = 0$, $x_2 = L_2$, $x_3 = 0$, $x_3 = L_3$. Second, the boundaries at the inlet Γ_{in} correspond to $x_1 = 0$ and the outlet is Γ_{out} corresponding to $x_1 = L_1$. Third, the interfaces between the different types of the domains: $\Gamma_{so} = \Omega_o \cap \Omega_s$, $\Gamma_{sp} = \Omega_p \cap \Omega_s$, and $\Gamma_{po} = \Omega_o \cap \Omega_p$. The first two interfaces are impermeable, whereas the third interface supports the fluid flow.

2.1 Fluid Flow

To simulate the coupled flow we suggest using the Navier-Stokes-Brinkman equation that accounts for the free flow in the open pores and the filtration flow in the microporous material [8,10]:

$$\begin{array}{l} \frac{1}{\phi}\frac{\partial \rho \vec{v}}{\partial t} = -\nabla p + \frac{2}{\phi}\nabla \cdot (\nu \varepsilon(\vec{v})) - \kappa^{-1}\vec{v} + \vec{F}, \\ \nabla \cdot (\vec{v}) = 0. \end{array} \tag{1}$$

In these notations $\vec{v}$ is the averaged velocity vector, p is the pressure, $\varepsilon(u) = \nabla\vec{u} + \nabla\vec{u}^T$ is doubled strain tensor, $\rho = \rho(x,t)$ is fluid density depending on the particular phase, $\nu = \nu(x,t)$ is fluid viscosity, also depending on the phase, $\kappa(x,t) = \kappa_0(x)\lambda$ is the permeability with κ_0 is the absolute permeability and λ is the mobility of the fluid, depending on the saturation of particular phase, ϕ is the porosity, $\vec{F}$ is the external forces including capillary forces. In this research, we neglected the non-linear term of the Navier-Stokes equation, because the flows in porous geomaterials are slow corresponding to low Reynolds numbers. Also, we excluded the gravitational forces, because they are negligible in comparison with the capillary forces at the micro-scale.

We also need to state the boundary conditions at all the boundaries:

$$\begin{array}{ll} \vec{u} = 0, & \vec{x} \in \Gamma_b, \\ \vec{u} = 0, & \vec{x} \in \Gamma_{so}, \\ \vec{u} = 0, & \vec{x} \in \Gamma_{sp}, \\ \vec{u} \cdot \vec{n} = U_0, & \vec{x} \in \Gamma_{in}, \\ \vec{u} \cdot \vec{\tau_1} = 0, & \vec{x} \in \Gamma_{in}, \\ \vec{u} \cdot \vec{\tau_2} = 0, & \vec{x} \in \Gamma_{in}, \\ p = P_0, & \vec{x} \in \Gamma_{out}, \end{array} \tag{2}$$

where $\vec{n}$ is a vector normal to the interface pointing inward to Ω, and $\vec{\tau}_j$ are two the tangential vectors. The first three conditions are no-flow conditions at the sides of the domain, and at the interfaces between the pores (either open or filled with microporous material) and the impermeable rock matrix. The last three conditions are stated at the inlet and outlet to support the fluid flow. Continuity of the velocity and pressure at the interface Γ_{op}; i.e., between the open and filled pores are satisfied implicitly by the Navier-Stokes-Brinkmann equation. The initial conditions are assumed to be zero.

2.2 Phase Transport in Open Pores

To simulate the phase transport in open pores we use the phase-field model [12,13,20]:

$$\begin{array}{l} \frac{\partial \psi}{\partial t} + \vec{u} \cdot \nabla \psi = \nabla \cdot (M(\psi) \nabla \mu), \\ \mu = F'(\psi) - \varepsilon^2 \Delta \psi, \end{array} \tag{3}$$

where $\psi \in [0,1]$ - is the order parameter defining the phase. The potential $F(\psi)$ is defined as

$$F'(\psi) = 2\psi(\psi-1)(2\psi-1).$$

This is the fourth-order in space differential equation, thus boundary value problem requires two boundary conditions at each boundary:

$$\begin{array}{ll} \nabla \mu \cdot \vec{n} = 0, \nabla \psi \cdot \vec{n} = -\frac{\sqrt{2}}{\varepsilon}(\psi^2 - \psi)\cos(\theta), & \vec{x} \in \Gamma_b \cup \Gamma_{so}, \\ \nabla \mu \cdot \vec{n} = 0, \nabla \psi \cdot \vec{n} = 0, & \vec{x} \in \Gamma_{out}, \\ \nabla \mu \cdot \vec{n} = 0, \psi = \Psi_{in}, & \vec{x} \in \Gamma_{in}. \end{array} \tag{4}$$

The first set of conditions are stated at the impermeable boundaries, and enforce the wetting angle equal to θ, which is measured for phase one; i.e., $\psi = 1$, see [16,21] for the details. The condition at the outlet allows the free outward transport of the phase. The third condition defines the distribution of the phases at the inlet. Note, that the condition at the interface Γ_{op} is missing. It is the subject of this research and it will be clarified below.

2.3 Transport in the Microporous Media

Transport of the two-phase fluid in porous media satisfies the Buckley-Leverett equation, typically written for the wetting phase:

$$\phi \frac{\partial S}{\partial t} + \nabla \cdot \left(\frac{\lambda_1(S)}{\lambda(S)} \vec{u} \right) + \nabla \cdot \left(\kappa \frac{\lambda_1(S)\lambda_0(S)}{\lambda(S)} \frac{dp_{01}}{dS} \nabla S \right) = 0. \tag{5}$$

where S is a saturation of the first (wetting) phase, $S \in [0,1]$. Parameters $\lambda_j = \kappa_{rj}/\nu_j$, are mobilities of the corresponding phases, total mobility is $\lambda = \lambda_0 + \lambda_1$, κ_{rj} is the relative permeability of phase j, which depends on the saturation, and ν_j is the viscosity of the phase j. Parameter p_{01} is the pressure difference between phases 0 and 1. The equation is stated in the domain Ω_p that is in the pores filled with microporous material. We need to state the boundary conditions:

$$\begin{array}{ll} \nabla S \cdot \vec{n} = 0, & \vec{x} \in \Gamma_b, \\ \nabla S \cdot \vec{n} = 0, & \vec{x} \in \Gamma_{out}, \\ \nabla S \cdot \vec{n} = 0, & \vec{x} \in \Gamma_{ps}, \\ S = S_0, & \vec{x} \in \Gamma_{in}. \end{array} \tag{6}$$

Same as before the conditions at Γ_{po} are required, which will be specified below.

Coefficients of Eq. (5) depend on the saturation. In this work, we use the following model. First, we assume that the saturation is bounded by the residual

saturation of each phase: $S \in [S_{r1}, 1 - S_{r0}]$. Note, that if the saturation equals S_{r1} the flow will transport only phase 1, thus only this phase will flow away from the microporous material. The same is valid for phase 0. The construct the equations of state we need to introduce the normalized saturation as:

$$S_j^N = \frac{1 - S_{jr}}{1 - S_{1r} - S_{2r}}. \tag{7}$$

After that, the relative permeability and the capillary pressure can be defined as:

$$\kappa_{jr} = \kappa_{jr}^{max}(S_j^N)^{a_j} \tag{8}$$

$$p_{01} = P_{c0}(S_1^N)^{-c}, \tag{9}$$

where κ_{jr}^{max} is the maximal phase permeability of the considered phase, P_{c0} reference pressure which may depend on the absolute permeability and porosity. Parameters a_j and c are chosen to match lab measurements.

3 Conjugation Conditions

Above, we described the models which are used to simulate the fluid flow and phase transport in open pores and the pores filled with a microporous permeable material. However, the goal of this research is to combine the model, to simulate coupled transport of the two-phase fluid.

Consider Cahn-Hilliard Eq. (3) and the Buckley-Leverett Eq. (5) and rewrite them in pseudo divergence-free form:

$$\begin{aligned} &\phi\tfrac{\partial q}{\partial t} + \nabla \cdot (f(q)\vec{u}) - \nabla \cdot (D(q)\nabla\mu) = 0, \\ &\mu(x < 0) = F'(q) - \varepsilon^2 \Delta q, \\ &\mu(x > 0) = q, \end{aligned} \tag{10}$$

where q represents either the normalized saturation S^N for the Buckley-Leverett equation or the order parameter ψ for the Cahn-Hilliard equation. The coefficients of the equation can be represented as follows:

$$f(q) = \begin{cases} q, & x < 0 \\ \lambda_1(q)/\lambda(q), & x > 0 \end{cases} \tag{11}$$

$$D(q) = \begin{cases} M(q), & x < 0 \\ -\kappa\frac{\lambda_1(S)\lambda_2(S)}{\lambda(S)}\frac{dp_{21}}{dS}, & x > 0 \end{cases} \tag{12}$$

$$\mu(q) = \begin{cases} F'(q) - \varepsilon^2 \Delta q, & x < 0 \\ q, & x > 0 \end{cases} \tag{13}$$

After that we may construct the conjugation conditions by introducing a closed contour containing the interface, integrating over the volume, and using the divergence theorem. This leads to the following conditions:

$$[f(q)] = 0, [D\tfrac{\partial \mu}{\partial n}] = 0.$$

The relations can be reformulated in the original notations as

$$\psi|_{0-} = \lambda_1(S)/\lambda(S)|_{0+},\ M\frac{\partial \mu}{\partial x}|_{0-} = -\kappa\frac{\lambda_1(S)\lambda_2(S)}{\lambda(S)}\frac{dp_{21}}{dS}\frac{\partial S}{\partial x}|_{0+}.$$

Note, that the Cahn-Hillard equation contains the fourth-order in space differential operator, thus additional equation is needed to close the problem:

$$\frac{\partial \psi}{\partial n} = -\frac{\sqrt{2}}{\varepsilon}(\psi^2 - \psi)\cos(\theta)|_{0-}. \tag{14}$$

This condition ensures the proper wetting angle of the fluid 1 at the surface Γ_{op}.

4 Numerical Scheme

To solve the coupled system of Eqs. (1), (3), and (5) we use the finite difference schemes on staggered grids, where pressure p_{i_1,i_2,i_3}, saturation S_{i_1,i_2,i_3}, order parameter ψ_{i_1,i_2,i_3}, and chemical potential μ_{i_1,i_2,i_3} are defined in integer grid points $(x_j)_{i_j} = h_j i_j$, where $j = 1, 2, 3$ and h_j is the grid step along x_j direction. Components of the velocity vector are stored in half-integer points in one spatial direction; i.e., $(v_1)_{i_1+1/2,i_2,i_3}$, $(v_2)_{i_1,i_2+1/2,i_3}$, $(v_1)_{i_1,i_2,i_3+1/2}$. After that, we applied the splitting technique to construct an almost explicit in time finite difference approximation of the entire problem.

Assume the solution is known up to the instant $t = t^n = n\tau$, where τ is the time step. We fix the coefficients of the Navier-Stokes-Brinkman equation:

$$\begin{gathered}\rho^n_{i_1,i_2,i_3} = q^n_{i_1,i_2,i_3}\rho_1 + (1 - q^n_{i_1,i_2,i_3})\rho_0,\\ \nu^n_{i_1,i_2,i_3} = (q^n_{i_1,i_2,i_3}\nu_1^{-1} + (1 - q^n_{i_1,i_2,i_3})\nu_0^{-1})^{-1},\\ \kappa^n_{i_1,i_2,i_3} = \kappa^0\lambda(q^n_{i_1,i_2,i_3}),\end{gathered} \tag{15}$$

where $q = \psi$ for $\vec{x} \in \Omega_o$, and $q = S^N$ for $\vec{x} \in \Omega_p$. Note, that density and permeability are defined in the integer points, whereas the Navier-Stokes-Brinkman equations are approximated in the half-integer points along one direction. Thus, we need further modify them using the arithmetic averaging over two adjoin integer points; i.e., $\rho^n_{i_1+1/2,i_2,i_3} = 0.5(\rho^n_{i_1+1,i_2,i_3} + \rho^n_{i_1,i_2,i_3})$, see [22,31] for the details.

4.1 Approximation of Navier-Stokes-Brinkman Equation

To solve the Navier-Stokes-Brinkman equation we use the projection-type scheme [9] with the further splitting of the Navier-Stokes and Brinkman terms:

$$\begin{gathered}\frac{\rho^n}{\phi}\frac{\vec{u}^* - \vec{u}^n}{\tau} = \frac{2}{\phi}\nabla_h \cdot (\mu^n \varepsilon_h(\vec{u}^n)) + \vec{F}^n,\\ \frac{\rho^n}{\phi}\frac{\vec{u}^{**} - \vec{u}^*}{\tau} = -(k^n)^{-1}\vec{u}^{**},\\ \frac{\rho^n}{\phi}\frac{\vec{u}^{n+1} - \vec{u}^{**}}{\tau} = -\nabla_h p^{n+1},\\ \nabla_h \cdot \vec{u}^{n+1} = 0,\end{gathered} \tag{16}$$

We omit the subscripts (i_1, i_2, i_3) in these equations, but use the notations ∇_h and ε_h to point out that the finite-difference operators, approximating the differential ones are used. Note, that the second equation, corresponding to the Brinkman term is approximated by the implicit scheme because the explicit one requires unacceptably small time stepping. The last two equations lead to the projection step which requires solving the Poisson equation for the pressure field. We use the Krylov-type iterative method with the original pseudo-spectral preconditioner to solve it [19]. The finite-difference operators approximating the spatial derivatives are second-order two-point central differences, and the approximation of the time derivatives is first-order accurate.

4.2 Approximation of Cahn-Hilliard Equation and the Buckley-Leverett Equation

Consider Eq. (10) representing the phase transport in a general form. We use the same staggered grid scheme to approximate it. We define the phase and the chemical potential in the integer grid points and the velocity components are stored in half-integer points. To approximate the advection term, one may use either upwind or WENO scheme [24,30]. The diffusion term may be approximated using the second-order central differences. Also, the Laplacian in the equation for the chemical potential is approximated with the second order. In general, we use explicit in time scheme:

$$\begin{aligned} &\phi\tfrac{q^{n+1}-q^n}{\tau} + \nabla_u \cdot (f(q^n)\vec{u}^{n+1}) - \nabla_h \cdot (D(q^n)\nabla_h \mu^n) = 0, \\ &\mu^n(x<0) = F'(q^n) - \varepsilon^2 \Delta_h q^n, \\ &\mu^n(x>0) = q^n. \end{aligned} \tag{17}$$

To approximate the boundary conditions< mainly the non-linear condition for the wetting angle, we use immersed boundary method [26].

4.3 Approximation of the Conjugation Conditions

To approximate the conjugation conditions, we do not need to consider them explicitly. Instead, we use the finite-difference approximation 17 throughout the entire computational domain $\Omega_o \cup \Omega_p$ with the coefficients defined according to formulae (11)–(13). However, the definition of the chemical potential μ inside the domain Ω_o requires evaluation of the Laplacian of the phase variable. Thus, an extra boundary condition has to be satisfied. We use the wetting-angle boundary condition (14) and approximate it using immersed boundary method [26] at the interface Γ_{op}.

5 Numerical Experiments

5.1 A Droplet on an Impermeable Surface

The first series of experiments was done to validate the algorithm. We considered a computational domain Ω being a cube with the side of $2 \cdot 10^{-4}$ m. The side

of the cube $x_1 = 0$ was the inlet, and the side $x_1 = 2 \cdot 10^{-4}$ was the outlets. The other four sides were impermeable. We placed an impermeable barrier for $x_1 \in [4 \cdot 10^{-5}, 6 \cdot 10^{-5}]$ m. The pressure difference between the inlet and outlet was equal to zero, i.e., no external flow was assumed. After that, we stated the initial conditions. We considered two types of initial conditions. First, phase 1 occupies the domain Ω_o except for the droplet of phase 0 which was a hemisphere of the radius of $4 \cdot 10^{-5}$ m, centered in point $(8 \cdot 10^{-5}, \cdot 10^{-4}, \cdot 10^{-4})$. Second, we performed the opposite situation; i.e., a droplet of phase 1 with a background of phase 0. In all our experiments we assume phase 1 is the wetting phase and measure the wetting angle with respect to it so that the wetting angle is always less than 90°. The other parameters of the fluids were fixed as provided in the Table 1. The simulations were done using the spatial steps equal to $2 \cdot 10^{-6}$ m. Thus the radius of the original droplet was only 20 grid points. We simulated the evolution of the droplet at the flat surface, which turned into a part of a sphere with a radius depending on the wetting angle. We measured the form of the droplet and the pressure drop according to estimates, presented in [25]. If the original droplet was a semi-sphere of radius R_0, the curvature radius of the final droplet will be

$$R_f = R_0 \left(\frac{2}{2 - 3\cos(\phi) + \cos^3(\phi)} \right)^{1/3}.$$

and the pressure difference is

$$\Delta P = \frac{2\sigma}{R_f},$$

where ϕ is the wetting angle.

Theoretical estimation of the pressure difference inside and outside of the droplet for different wetting angles are presented in Table 2. Note, that the error in pressure estimation may reach up to 5% for wetting angles between 30° and 120°, but it may approach 7% for small wetting angles. In our opinion, this may be caused by poor resolution of the droplet, especially taking into account the size of the droplet in comparison with the interfacial tension. To illustrate the solution to the considered problems, we provide 2D cross-sections of the solution corresponding to the wetting angles of 60° and 120° in Fig. 1. Additionally, we plot the sectors of the sphere, that the droplet suppose to form, and the lines corresponding to the considered wetting angles to illustrate a good agreement of the experiments with the theoretical estimates.

Table 1. Fluid parameters.

	Phase 1	Phase 0
viscosity, ν (Pa/s)	$3.8 \cdot 10^{-4}$	$4.027 \cdot 10^{-3}$
mass density, ρ (kg/m^3)	1000	880
interfacial tension σ_{10} N/m	$2.571 \cdot 10^{-2}$	

Table 2. Theoretical estimation (ΔP_t) and simulations results (ΔP_e) of the pressure difference inside and outside of the droplet placed at a flat surface for different wetting angles.

angle	R_f (m)	ΔP_t (Pa)	ΔP_e (Pa)	angle	R_f (m)	ΔP_t (Pa)	ΔP_e (Pa)
20	$22.8 \cdot 10^{-5}$	224.8	219	160	$3.18 \cdot 10^{-5}$	1618.2	1703
25	$11.7 \cdot 10^{-5}$	300.4	295	155	$3.18 \cdot 10^{-5}$	1616.2	1701
30	$13.5 \cdot 10^{-5}$	379.5	376	150	$3.19 \cdot 10^{-5}$	1612.7	1697
35	$11.2 \cdot 10^{-5}$	460.9	461	145	$3.20 \cdot 10^{-5}$	1607.1	1693
40	$9.46 \cdot 10^{-5}$	543.8	547	140	$3.22 \cdot 10^{-5}$	1598.9	1690
45	$8.20 \cdot 10^{-5}$	627.1	633	135	$3.24 \cdot 10^{-5}$	1587.7	1680
50	$7.24 \cdot 10^{-5}$	710.2	719	130	$3.27 \cdot 10^{-5}$	1572.8	1658
55	$6.49 \cdot 10^{-5}$	792.1	805	125	$3.31 \cdot 10^{-5}$	1553.8	1633
60	$5.89 \cdot 10^{-5}$	872.3	889	120	$3.36 \cdot 10^{-5}$	1530.5	1607
65	$5.41 \cdot 10^{-5}$	950.2	971	115	$3.42 \cdot 10^{-5}$	1502.3	1574
70	$5.02 \cdot 10^{-5}$	1025.0	1049	110	$3.50 \cdot 10^{-5}$	1469.2	1533
75	$4.69 \cdot 10^{-5}$	1096.4	1126	105	$3.59 \cdot 10^{-5}$	1431.0	1493
80	$4.42 \cdot 10^{-5}$	1163.9	1198	100	$3.71 \cdot 10^{-5}$	1387.7	1439
85	$4.19 \cdot 10^{-5}$	1227.0	1266	95	$3.84 \cdot 10^{-5}$	1339.1	1384

5.2 A Droplet on a Porous Surface

The second series of experiments was done for the droplet placed on the flat surface of porous material. We used the results of the previous simulations with formed droplets with proper wetting angles as the initial conditions. The size of the domain and the grid steps were the same as before. We changed the impermeable barrier for $x_1 \in [4 \cdot 10^{-5}, 6 \cdot 10^{-5}]$ m to the homogeneous porous material with porosity equal to 0.1 and absolute permeability $\kappa_0 = 10^{-13}\ m^2$ which is approximately 0.1 Darcy. The parameters of the Buckley-Leverett model are provided in Table 3. The pressure difference between the inlet and outlet was equal to zero. Model time was $1.35 \cdot 10^{-3}$ s. Note, that the initial saturation of the porous material was S_{1r} if the background was filled with phase 0, and $1 - S_{0r}$ if the background corresponded to phase 1.

Table 3. Parameters of the Buckley-Leverett model.

	Phase 1	Phase 0
k_{jr}^{max}	0.31	0.91
a_j	2.585	1.552
S_{jr}	0.38	0.26
P_0	$9 \cdot 10^4$	
c	0.246	

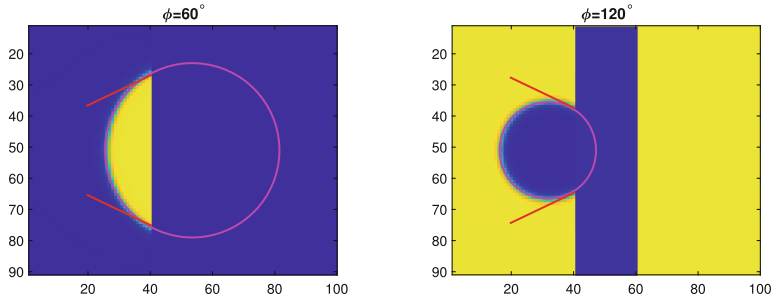

Fig. 1. 2D cross-sections of the droplets on an impermeable surface corresponding to wetting angles equal to 60° (left) and 120° (right). The circle represents the cross-section of the theoretically predicted droplet shape. The inclination of the lines corresponds to the wetting angles. Axes are in grid points.

In Figs. 2 and 3 we provide snapshots of the solution at different time instants for the models with the wetting angle 60° and 120°, respectively. If the fluid of the droplet is a wetting phase, the porous material starts absorbing the droplet, due to the capillary forces. Note, that the droplet preserves the shape and the wetting angles whereas its volume is reduced. This is due to the use of static wetting angles in the conjugation conditions. When the droplet of the non-wetting phase is considered (Fig. 3) some fluid starts to saturate the porous material at the very first instants. This is happening due to the pressure difference inside and outside of the droplet. However, the capillary pressure in the porous material growing with saturation and equilibrates the external force. As a result the droplet slightly reduces in size but preserves the shape and wetting angles.

5.3 A Droplet on a Porous Surface with External Flow

The third series of experiments are done for the same setup as the previous one. However, we added a positive pressure drop between the inlet and outlet, so that $\Delta P = 10^5$ Pa. In this case, the average fluid flow velocity in the x_1 direction was 0.1 m/s. Simulation time was $1.35 \cdot 10^{-3}$ s, thus approximately half of the pore volume was injected. The snapshots with wetting and non-wetting droplet are presented in Figs. 4 and 5 respectively.

If a droplet of wetting fluid is considered, the filtration process is fast, so that the snapshots are presented at earlier instants, than in all other considered cases. Note, that the wetting fluid tends to saturate the porous material and only a relatively small part of it flows out. Moreover, the non-wetting phase flowing out of the porous material start forming a droplet inside the wetting phase until the wetting phase breaks away. The volume of the bubble of the wetting phase is much smaller than that at the initial stage because it is partially locked by the capillary forces inside the porous material. An opposite situation is observed if the non-wetting phase forms a droplet on the porous material. The non-wetting phase is forced to filtrate through the porous layer. Almost no diffusive spreading

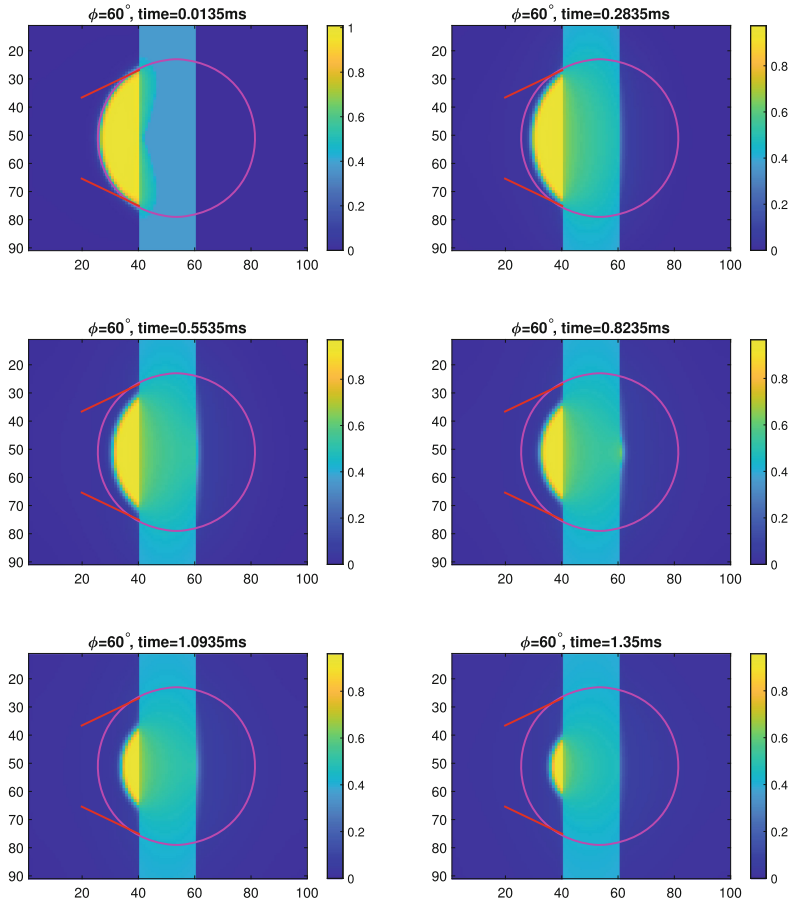

Fig. 2. 2D cross-sections of the droplets on a porous barrier corresponding to wetting angles equal to 60° at different time instants. The circle represents the cross-section of the theoretically predicted droplet shape on an impermeable surface.

of the non-wetting phase is observed in tangential directions inside the porous layer so the external flow is the major transport factor. When breaks through the porous layer, the non-wetting phase forms a spherical bubble, opposite to the filtration of the wetting phase.

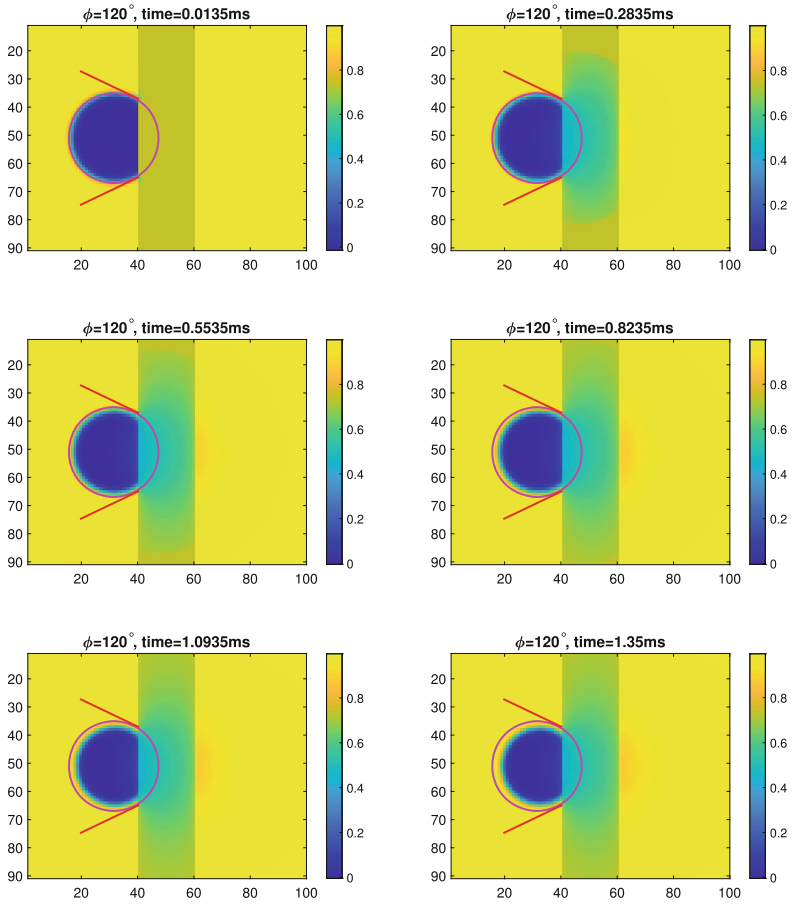

Fig. 3. 2D cross-sections of the droplets on a porous barrier corresponding to wetting angles equal to 120° at different time instants. The circle represents the cross-section of the theoretically predicted droplet shape on an impermeable surface.

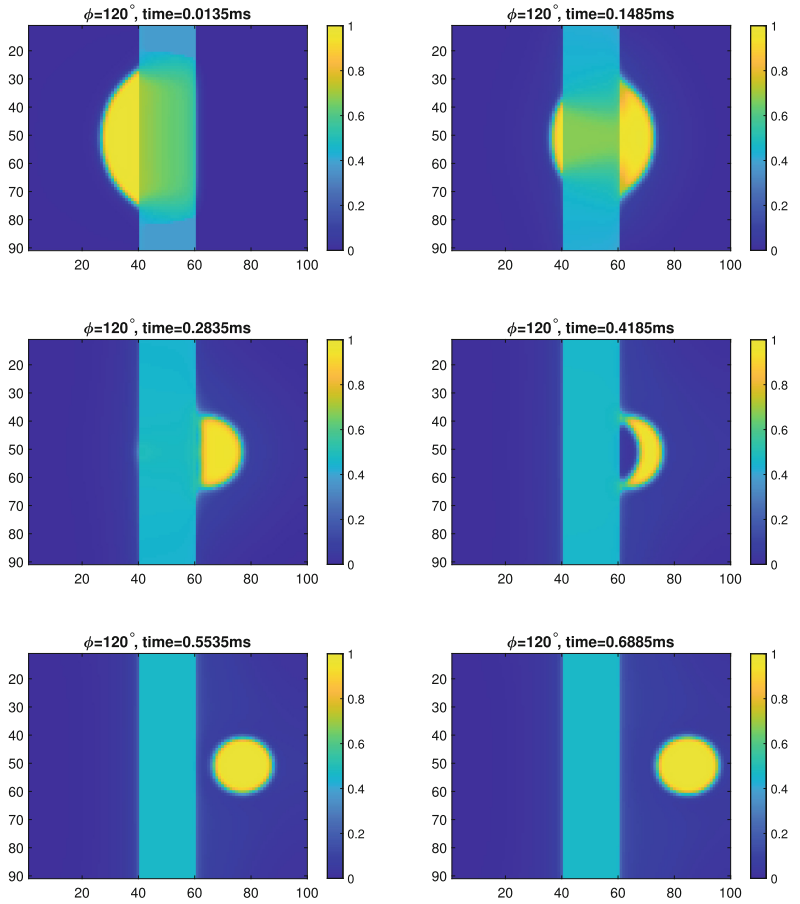

Fig. 4. 2D cross-sections of the droplets on a porous barrier corresponding to wetting angles equal to 60° at different time instants. Experiment with the external flow.

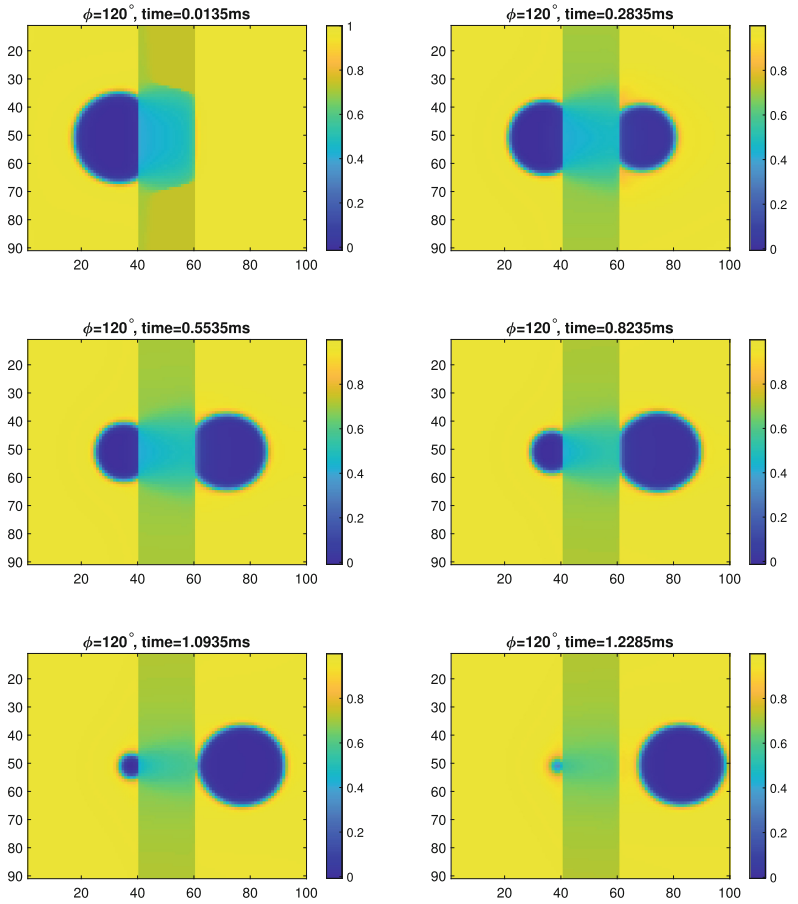

Fig. 5. 2D cross-sections of the droplets on a porous barrier corresponding to wetting angles equal to 120° at different time instants. Experiment with the external flow.

6 Conclusion

We presented an original numerical algorithm to simulate coupled two-phase fluid flow in domains containing open pores and microporous material. Free flow is simulated in the open pores and the Darcy filtration flow is assumed in the microporous subdomains. To simulate the coupled flow we used the time-dependent Navier-Stokes-Brinkman equation. The transport of the phases is governed by the Cahn-Hilliard equation in the open pores and by the Buckley-Leverett equation in the porous material. We suggested a unified finite-difference approximation of the two transport equations, that satisfy the natural conjugation conditions. However, Cahn-Hilliard requires an additional boundary condition, that must be satisfied at the interface to ensure the wetting angle. The derived coupled system is approximated by the finite-differences

with the explicit approximation of the Navier-Stokes equation and Cahn-Hilliard-Buckley-Leverett equations. However, an implicit approximation of the Brinkman part is applied. The algorithm is implemented in 3D using CUDA technology. According to the presented numerical experiments the algorithm is capable of simulating the saturation of the porous materials and breaking one phase through the porous material, forming droplets after breaking away.

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Numerical Dispersion Mitigation Neural Network with the Model-Based Training Dataset Optimization

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Abstract. A neural network is used to approximate the transition operator from seismic data modeled on a large computational grid to data obtained on a small one. Thus, we obtain an effective way of suppressing numerical dispersion in numerically modeled seismic fields. This article discusses a method for constructing an optimal training dataset based on the properties of a velocity model. We build a distance matrix for the parts of the model that correspond to the positions of the sources and build a dataset in such a way that the distance between the training set and all sources is limited.

Keywords: Deep learning · seismic modelling · numerical dispersion

1 Introduction

The primary method for solving a system of elastodynamic equations is the finite difference method [16]. However, its use often leads to numerical dispersion in the solution, which may be inappropriately high if a coarse grid is used. Numerical dispersion in seismic modeling is a specific type of numerical error that appears in the odd-order derivatives present in the approximation error of the differential operator. To suppress the numerical dispersion, several pre-processing and post-processing algorithms were suggested [11]. However, they are computationally intense. Moreover, they can treat the dispersion caused by the discretization of the temporal derivatives, whereas mitigation of spatial dispersion is still an unsolved problem.

Indeed, advanced numerical methods may be applied to improve accuracy. These include the high-order finite-difference schemes, optimization schemes that

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suppress the numerical error [9], the discontinuous Galerkin method and spectral element methods[5,8,14]. The above methods do not necessarily lead to a reduction in computational complexity. As the order of approximation increases, the number of operations and the memory used increases.

A different approach which was recently suggested is based on the use of machine learning methods to suppress numerical dispersion [2,3]. The idea of the approach is to approximate a nonlinear transition operator from synthetic data calculated on a coarse grid to data modeled on a fine grid using the machine learning technique. This approach makes it possible to suppress variances and artifacts to a large extent with less memory and time consumption than the other post-processing techniques.

However, building a neural network is a challenging task that requires careful consideration of various factors. One such factor is the selection of appropriate hyperparameters. This can be a time-consuming process as it involves a lot of trial and error. Another critical aspect of constructing neural networks is the creation of an optimal training dataset. A well-designed dataset can provide a high degree of generalization, enabling the network to perform well on unseen test data. The importance of creating a good dataset cannot be overstated, as the neural network's ability to learn and make accurate predictions heavily depends on the data it is trained on. This work aims to create a representative sample for training a neural network.

2 Seismic Modeling

The seismic data we use in this research was obtained by solving the elastic wave equation defined in a 2D unbounded domain. We are using the finite difference method to numerically solve a set of these equations with different right-hand sides (sources). The entire dataset is generated using a coarse enough mesh with fewer than 5 points per dominant wavelength. The coarse grid solution can be generated relatively fast. The training dataset includes the seismograms, which are simulated using fine enough mesh, i.e., with 10 or more grid points per wavelength. Generating this dataset takes most of the computational time, thus we need to minimize the number of seismograms in this dataset. In both cases, the formal problem can be stated as:

$$L[\boldsymbol{w}(t,\boldsymbol{x})] = \boldsymbol{f}(t,\boldsymbol{x}^{\boldsymbol{s}}),$$

where $\boldsymbol{w}-$ the solution of elastic wave equation, $\boldsymbol{f(t,x^s)}$ is the time-dependent right-had size or external forces, $\boldsymbol{x^s}$ is the source position. Also, from this problem we get the velocity components on the receiver's positions

$$\boldsymbol{w_s}(t,\boldsymbol{x}^{\boldsymbol{r}}),$$

where $\boldsymbol{x^r}$ is the receiver positions.

And, for a finite-difference approximation of the differential operator with the fourth-order of approximation in space and second-order in time, we can rewrite our problem as

$$L_h[\boldsymbol{w_h}] = \boldsymbol{f_h}(t,\boldsymbol{x}^{\boldsymbol{s}}),$$

where $\boldsymbol{f_h}$ is the approximation of the right-hand side, $\boldsymbol{u_h}$ is the finite-difference solution corresponding to the grid with the step h.

According to the general theory of the finite difference schemes, if two grids with steps h and H so that $h < H$ are considered, then the errors

$$\|\boldsymbol{w}_h - [\boldsymbol{w}]_h\| \leq \varepsilon_h, \|\boldsymbol{w}_H - [\boldsymbol{w}]_H\| \leq \varepsilon_H,$$

satisfy the inequality $\varepsilon_h < \varepsilon_H$. So, we manage to construct a map $\boldsymbol{w}_{ML} = G[\boldsymbol{w}_H]$ that transforms the coarse grid data to the fine grid data with appropriate accuracy; i.e., $\|\boldsymbol{w}_{ML} - \boldsymbol{w}_h\| = \varepsilon_{ML} << \varepsilon_H$, we may significantly improve the coarse mesh solution without simulation of the entire dataset on a fine mesh.

3 Network Architecture

We apply a neural network based on U-net architecture [15] to translate data modeled on a coarse grid into data modeled on a fine grid. The U-net architecture is composed of an encoder and a decoder. The encoder captures the context of the image by reducing the spatial resolution of the input image through a series of convolutional and pooling layers. The decoder then recovers the original spatial resolution by using a series of deconvolutional and upsampling layers. This network, called here as NDM-net (Numerical Dispersion Mitigation Network), contains 16 convolutional layers: 8 upsampling layers and 8 concatenation layers. The depth of the network was set according to the dimensions of the input images. The layers consist of the convolution operator, the batch normalization operator, and the Rectified Linear Unit (ReLU) as the activation function. At the convolutional stage, layers have LeakyRelu instead of ReLu with a negative slope factor of 0.2. Figure 1 shows the U-net architecture. Dropout is used to reduce overfitting and generalization errors as well as early stopping.

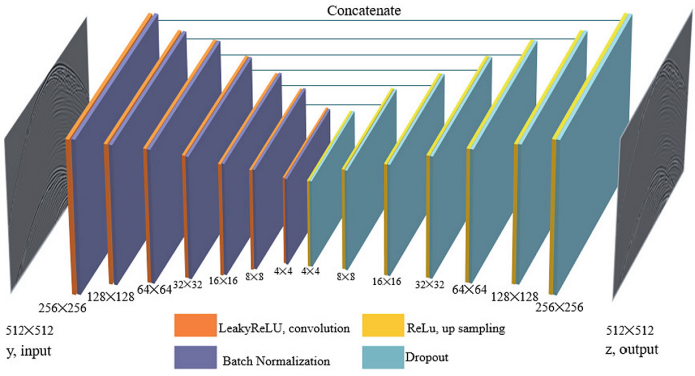

Fig. 1. U-net architecture

Let $(Y, Z) = \{y_i, z_i\}_{i=1}^N$ be training pairs consisting of the N-th number of seismograms modeled on a coarse grid and a fine grid, respectively.

The NDM-net learns all the parameters of the model by minimizing the loss function, defined as following

$$L = \sum_i ||G(y_i) - z_i||_1$$

where $G : y_i \rightarrow z_i$ is the generated set of seismograms.

The update of the parameters occurs according to the chain rule and is derived as

$$\theta_l = \theta_l - \gamma(\delta l / \delta \theta_l),$$

where γ is the learning rate, which changes its value with the system's evolution, and $\delta l / \delta \theta_l$ is acquired from the last layer to layer l by the chain rule.

It should be noted that the results of training a neural network are highly dependent on the input data. Therefore, it is difficult to talk about the applicability of this architecture for various noisiness.

Also, the choice of a neural network is not limited to this network, we believe that cGan [6,10], pix2pix [4] and others can be promising architects in the seismic data processing. There are many applications of neural network in seismic data processing and interpretation, some use deep convolutional neural network (CNN) for denoising and ground-roll noise attenuation [7,17], another use cycle-Gan, cGan for interpolation[6,12], etc.

4 Input Data

We simulate the seismic data set using the BP subsurface model shown in Fig. 2. This model was built on a $12.5m \times 6.25m$ grid and had a size of 67 km long and 12 km deep. The velocity V_p varies from 1430 m/s to 4790 m/s.

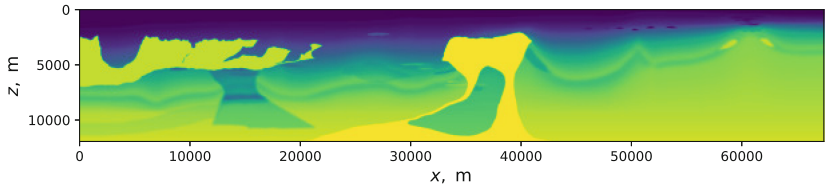

Fig. 2. BP model

The right part of the model consists of a simple background and slowly changes. In contrast, the central and left part is more complex and have a salt body and sharp velocity.

The acquisition included 2696 sources with a distance of 25 m. We recorded the wavefield by 2401 receivers for each shot with maximal source-receiver offsets of 15 km. The receivers were 12.5 m apart from one another. For this model, we

generated seismograms using a grid with a step h_x of 6 m (coarse grid) and 3 m (fine grid). The source function was the Ricker wavelet with a center frequency is 30 Hz. The time sampling step is 3 ms.

We cropped seismograms to 512×512 points as shown in Fig. 3.

5 Training Dataset Construction

An important stage of neural network training is the creation of the training dataset. This section presents three methods for constructing training datasets and evaluating their effectiveness. In order to assess whether the generalization to the test data is sufficiently well carried out, we will use the Normalized Mean Squared Error (nMSE). The nMSE is defined by the following expression

$$nMSE(y_i, z_i) = \frac{1}{2} \frac{\|y_i - z_i\|_2}{\|y_i\|_2 + \|z_i\|_2}.$$

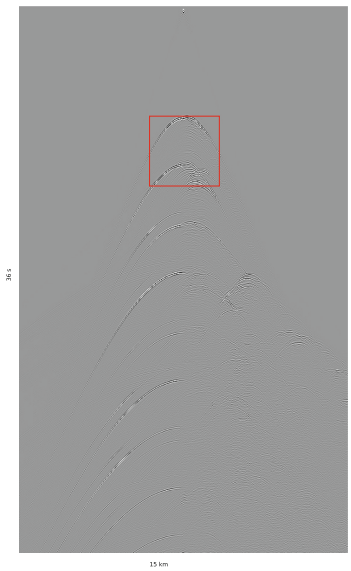

Fig. 3. A example of a seismogram. The red rectangle corresponds to the cropped zone. (Color figure online)

We also need to introduce the average error between two datasets containing the same number of samples:

$$R(Y, Z) = \frac{1}{N} \sum_i nMSE(y_i, z_i).$$

This formula is used throughout the paper to estimate the distance between the coarse and fine-grid data, as well as between the generated dataset $U^{ML} = \{G(y_i)\}_{i=1}^N$ and dataset Z modeled on a fine grid.

5.1 Equidistantly Distributed Sources

The simplest sampling option is to include seismograms with correspond to equidistantly distributed sources to cover various combinations of input variable values. The set of indices for such a training dataset is designed as follows:

$$J_k^{eq} = 1, k, 2k, ..., q(k)k,$$

where $k \in \mathbf{N}$, $k > 1$, and $q(k) = [N/k]$ that is the integer part of the ratio.

We constructed three datasets for the BP model: $D_{10}^{eq}, D_5^{eq}, D_{2.6}^{eq}$, which corresponds to datasets with $10\%, 5\%, 2.6\%$ of the total number of sources, respectively.

The number of seismograms in the training data, the average error between the generated set and set Y, and the distance between the initial sets for each dataset are given in Tables 1 and 2.

Table 1. Description of the datasets with equidistantly distributed for the BP model

Dataset	Number of sources	$R(U^{ML}, Z)$
$D_{2.6}^{eq}$	68	0.206
D_5^{eq}	135	0.168
D_{10}^{eq}	270	0.138

Table 2. Description of all dataset for the BP model

Dataset	Length of all dataset	R(Y,Z)
Initial	2696	0.469

5.2 Model-Based Dataset

In our previous research [1] we illustrated that the seismograms corresponding to closely spaced sources are similar. Moreover, the similarity of the seismograms correlates with the similarity of the model where the wavefield propagates. In this paper, we consider the models for which the seismogram is generated and construct the training dataset that corresponds to the most typical models. Note that the original model is elongated in a horizontal direction, exceeding the active acquisition system for a fixed source position. Thus, we may restrict the model for a particular source position $\boldsymbol{x}_j^s$ by the size of the active acquisition. As a result, we may consider a set of models $\mathrm{M} = \{M_1, ..., M_{N_s}\}$ with the number of models equal to the number of sources.

For example, the distance between M_{j+1} and M_j is calculated by the Normalized Mean Squared Error. Thus, a distance matrix was obtained (Fig. 4), which shows how the model changes depending on the distance between the sources.

Then, we suggest building the training sample in such a way as to limit the maximum distance between the entire data set and the training set.

So, we have a max-min problem:

$$\max_{k\in 1,..,N} \min_{j\in J_t} nMSE(M_k, M_j) \leq Q,$$

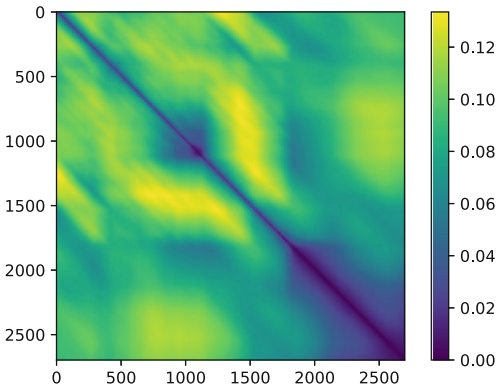

Fig. 4. Distance matrix

where J_t is a set of training dataset sources indices and Q is the desired error level.

Thus, the obtained data sets (Fig. 5) are dense in the areas where the model is highly variable in the horizontal direction, but they are sparse where the model is close to the horizontally layered. Description of the samples used and errors are presented in the Table 3

Table 3. Description of the datasets with L_2-preserving for the BP model

Dataset	Number of sources	$R(U^{ML}, Z)$
$D^M_{2.6}$	70	0.223
$D^M_{4.9}$	133	0.159
$D^M_{10.2}$	275	0.136

5.3 Comparison of the Sampling Techniques

We will use nRMS, as well as the Structural Similarity Index (SSIM) [13], to check the similarity of the generated seismograms with the original ones[1]. The last metric deals with the structural elements of images. SSIM is calculated for

[1] We can add other metrics.

each overlapping image block using a pixel-by-pixel sliding window, and therefore it can provide a distortion/similarity map in the pixel domain. The following equation determines this metric

$$SSIM(x_i, y_i) = \frac{(2\mu_x\mu_y + C_1) + (2\sigma_{xy} + C_2)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_2)}$$

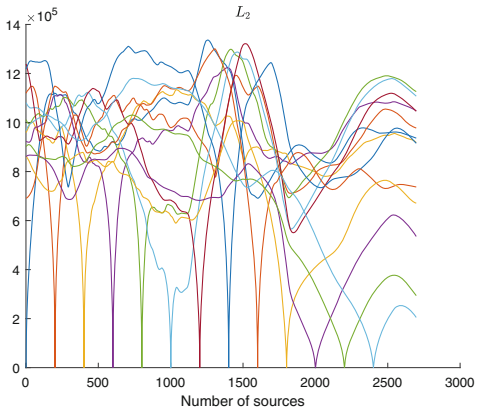

Fig. 5. The L_2 distances between the parts of the model as a function of the distance between the sources for BP model

where μ_x and σ_x are the mean intensity and standard deviation of x_i,μ_y and σ_y are the mean intensity and standard deviation of y_i, σ_{xy} is the covariance of x_i and y_i, C_1 and C_2 are the constants in order to maintain stability. The closer this indicator is to one, the more similar the seismograms are. The above metric is used to compare a set of samples, the average values for all training sets are shown in the Table 4

Table 4. SSIM

Dataset	$SSIM(U^{ML}, Y)$
$D^M_{2.6}$	0.993
$D^M_{4.9}$	0.996
$D^{eq}_{2.5}$	0.994
D^{eq}_{5}	0.995

Another metric for evaluating the effectiveness of a neural network on different samples is nMSE (Fig. 6)

Compared to results obtained using equidistant sources, the optimized datasets provide a smaller error for a given number of training data. Note that

the greater the number of seismograms in the set for all types of samples, the more accurate the results. However, the training results on an optimal sample provide less benefit when the distance matrix has a value close to zero, even with a large amount of training data.

6 Numerical Results

In this section, we present the result of our experiments, obtained from applying the neural network to the data described above. In order to show what the generated traces look like, we take the simplest way to construct the training set - equidistantly distributed sources. The networks are trained on a workstation with one NVIDIA GeForce RTX 3090 with 8 GB memory and Intel Core CPU with 256 GB RAM.

In order to show a qualitative result, we take the most optimal training set D_{10}^{eq}. The neural network takes 3 seconds to train one epoch on GPU. An early stop to prevent overfitting was at epoch 500. Thus, it will take at least 30 minutes to get acceptable results. While the application of a neural network to test data requires less than a second.

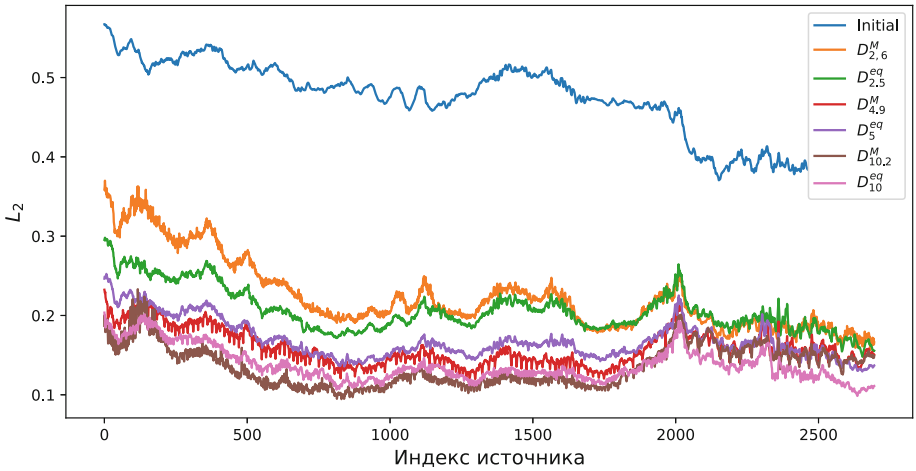

Fig. 6. The pair-wise L_2 distances between the fine-grid data and the NDM-net predicted data for different datasets.

Figure 7 shows traces, one of which is generated by a neural network $G(y)$ and the other two are reference ones. Below, in Fig. 8, the difference between generated trace and z is presented, as well as difference between y and z.

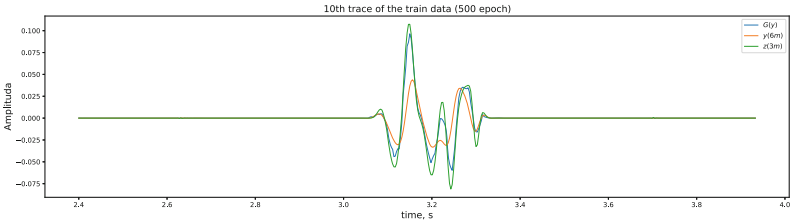

Fig. 7. Seismic traces $y(6m)$ and $z(3m)$ and generated trace $G(y)$ by NDM-net

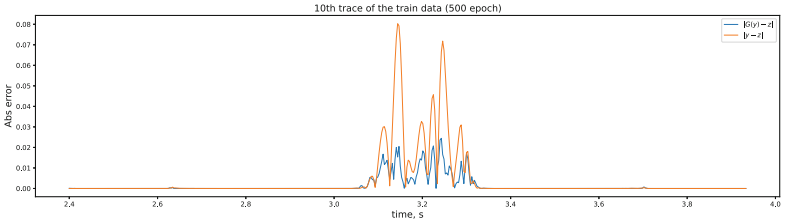

Fig. 8. Difference between generated trace $G(y)$ and trace $z(3m)$ and difference between reference data

7 Conclusion

We used a neural network to suppress numerical dispersion in seismic data. Specifically, we approximated the transition operator from data modeled on a coarse grid to data modeled on a fine grid. Our training results demonstrate that this method effectively detects correlation noise, numerical dispersion and suppresses a significant portion of numerical errors.

We created an optimal training set to improve the neural network's performance and speed up learning. Suppose we choose the training set so that the number of seismograms in it is minimal and at the same time representative, then we will get more efficient results. In this study, we consider two approaches to constructing a training dataset: a method based on equidistantly distributed sources and a method that constructs an optimized sample based on the properties of the velocity model.

The second method to construct the training dataset is limiting the distance calculating for the parts of the model that correspond to the positions of the velocity model. We are assumed to choose a limiting value and thus construct a set of sources and their corresponding seismograms.

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Frequency Domain Numerical Dispersion Mitigation Network

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Abstract. This study proposes using an NDM-net in the frequency domain to mitigate numerical dispersion in seismic data, a major problem in the petroleum industry. Frequency-domain processing has several advantages over time-domain processing, including more efficient extraction of information from large datasets, noise removal, and correction for amplitude and phase distortions. The proposed approach can significantly improve the exploration and characterization of hydrocarbon reservoirs, with Full Waveform Inversion (FWI) being a prominent example. To evaluate the proposed method, we applied it to a realistic synthetic BP numerical example, resulting in an average reduction of numerical dispersion by a factor of three and an order-of-magnitude increase in calculation performance. The proposed approach enables us to process the entire seismogram simultaneously, in contrast to the time-domain NDM-net implementation and thus can be applied to 3D seismic modeling. Overall, the use of NDM-net in the frequency domain can significantly improve the quality and efficiency of seismic data processing, enhancing our understanding of hydrocarbon reservoirs and facilitating more accurate exploration and characterization of subsurface structures.

Keywords: Frequency domain · deep learning · seismic modelling · numerical dispersion · Fourier transform

1 Introduction

Simulating the wave field for a single seismic source takes several thousand core hours using conventional numerical modeling [15]. However, the acquisition system consists of thousands of seismic sources, resulting in high computational

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costs. To address this issue, one possible approach is to reduce the dimension of the problem by decreasing the number of degrees of freedom or grid nodes. One way to achieve this is to increase the spatial grid step. Nonetheless, this leads to a numerical error, which frequently appears as numerical dispersion, especially when even-order approximations are used [1,10].

Deep learning has revolutionized the field of seismic processing by enabling automated, and more accurate interpretation of seismic data [17]. Seismic data is complex and multidimensional, and traditional processing methods have limitations in identifying subtle features and patterns in the data. Deep learning algorithms can automatically learn from large amounts of labeled data and identify patterns in seismic data that may be difficult for humans to detect [5]. This can lead to improved seismic imaging, better reservoir characterization, and more accurate predictions of subsurface properties. Deep learning also has the potential to reduce processing time and costs, making seismic exploration more efficient and cost-effective. Using machine learning methods to post-process seismic data seems promising, as suggested in the articles [6,13]. [4] describe an NDM-net artificial neural network that suppresses numerical dispersion. This deep neural network (DNN) is designed to suppress numerical dispersion in precalculated wave fields recorded at the free surface.

To generate realistic seismic data, wave fields must be computed for many source positions, typically on the order of 10^4. In such cases, seismograms for neighboring sources exhibit very slight differences [3]. A solution that closely approximates the actual one is employed as a representative dataset for training an artificial neural network to address this peculiarity of seismic modeling problems. This solution is obtained using a very fine grid, corresponding to a relatively small number of initial source positions. In a previous paper, [4], this approach was applied to two-dimensional models, and it was demonstrated that using seismograms from 10% of sources equidistantly distributed relative to each other as a training sample and post-processing them with a neural network, can significantly reduce the numerical error in data computed on a coarse grid. This approach reduces the time required to calculate the complete set of seismograms.

Treating seismic processing in the frequency domain involves analyzing seismic data in terms of its frequency content, providing numerous advantages over time-domain processing. By separating the different frequency components of the seismic signal, the frequency-domain method can help to identify subsurface features that may be difficult to detect in the time domain [16]. Additionally, frequency-domain methods can improve data quality by removing noise and correcting for amplitude and phase distortions caused by the seismic acquisition system [2,18]. Another benefit is that frequency-domain processing provides a more efficient way to extract information from seismic data, mainly when dealing with large data sets. Geoscientists can gain valuable insights into the subsurface by transforming seismic data into the frequency domain, leading to more accurate predictions about hydrocarbon reservoirs' location, size, and properties.

Frequency domain processing plays a critical role in modern seismic processing and can significantly improve the exploration and characterization of

hydrocarbon reservoirs by removing noise and distortions that may obscure essential features in the data. Moreover, much seismic processing is done in the frequency domain, with Full Waveform Inversion (FWI) being a prominent example [11]. FWI is closely related to seismic modeling and is often used in the time-frequency domain to better resolve subsurface structures and properties, leading to more accurate and detailed imaging results [14]. In this work, we present the application of NDM-net to seismic data in the frequency domain, highlighting the importance of using frequency-domain processing techniques in seismic exploration and imaging.

2 Theory and Method

2.1 Frequency Domain

We require fewer samples to work with seismic data in the frequency domain than in the time domain. To demonstrate this, we consider a typical synthetic reflection data shown in Fig. 1,A. It was modeled using an acoustic approximation with a Ricker source wavelet having a dominant frequency of 25Hz. The seismogram has a time step of 3ms and a length of 6s. The non-zero part of its Fast Fourier Transform (FFT) is presented in Fig. 1,B and C. The zoomed-in FFT for trace index 200 (vertical red line in Fig. 1,B) is plotted in Fig. 1,F and G. We can observe that only 512 frequency samples (red rectangle in Fig. 1,F and G) contain all the non-zero parts of the FFT signal.

To demonstrate this, we take this part's inverse FFT (IFFT) of the data (expanding all missing samples in the real and imaginary FFT parts using the zero value) and compare it with the original seismogram. The corresponding IFFT results and the difference with the original seismogram are presented in Fig. 1,C and D, respectively. One may observe that we don't lose information during these forward and inverse Fourier transforms. Similar property of FFT spectra of the solution of finite-difference problems is widely used in numerical simulations, including FFT-based data interpolation [9] and FFT-based preconditioners to solve Poisson equation [7].

In previous work [4], we could not process the full seismogram simultaneously due to GPU memory amount restrictions and had to split it in the time direction so that the processed part of the data had 512 time samples. Usually, in seismic modeling, we use a Ricker wavelet as a signal signature with a peak frequency of about $25 - 30$Hz, as the seismic data is band-limited, meaning that in the time-frequency domain, the primary energy of the signal is concentrated in a bounded band around the source peak frequency. In what follows, we will operate on the premise that synthetic seismic data is essentially band-limited.

2.2 NDM-Net in Frequency Domain

This study employs the NDM-net, which was introduced in [4]. This artificial neural network modifies the U-net, a fully convolutional neural network, as

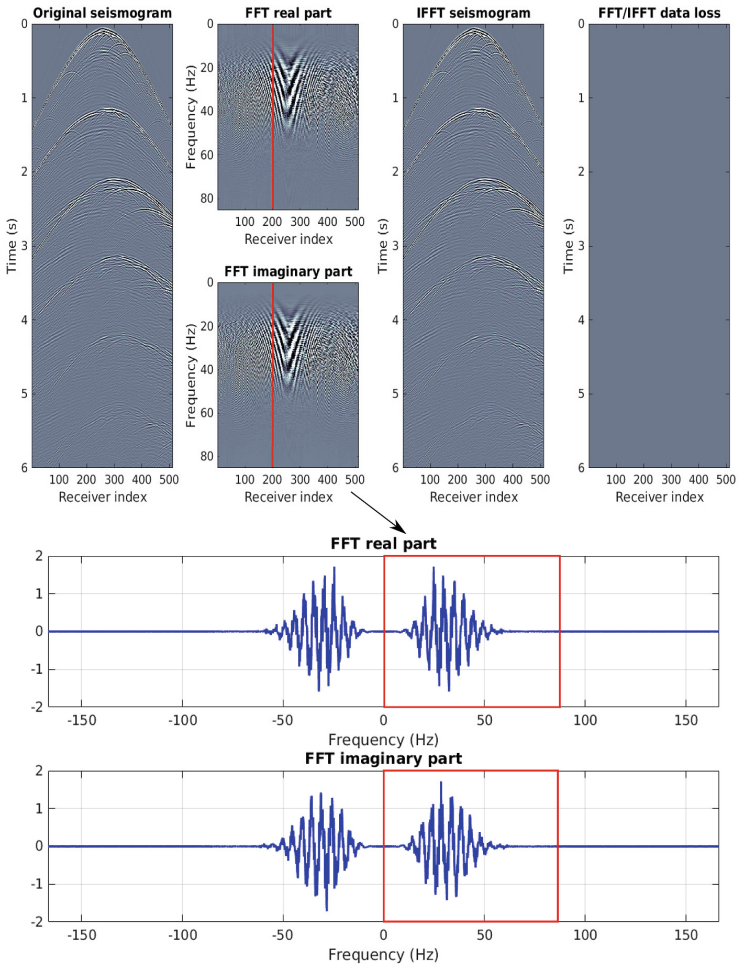

Fig. 1. The demonstration of time to frequency domain seismic data transform. The original seismogram (A), its Fourier transform (B), (C), and inverse Fourier transform (D). The difference between (A) and (D) is shown in plot(E) and demonstrates no loss of information during the time-frequency conversion. On the bottom, we present a particular trace in the frequency domain with index 200 (see vertical red line on (B), (C): real part (F) and imaginary part (G). The red rectangle demonstrates the part of the signal in the frequency domain used for data storing. (Color figure online)

described in [12]. The NDM-Net comprises 16 convolutional layers, eight upscaling layers, and eight concatenation layers, as illustrated in Fig. 2. The input and output tensors' dimensions are $512 \times 512 \times 2$. The activation function used for the first eight convolutional layers responsible for encoding or feature extraction is ReLU (linear rectification). For the last eight layers, representing the decoder part, the activation function used is LeakyReLu (linear rectification

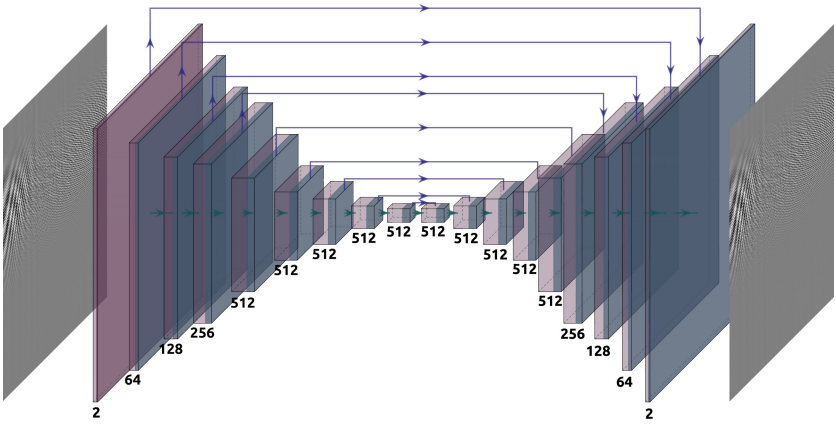

Fig. 2. FD NDM-net convolutional neural network architecture diagram. A convolutional neural network transforms frequency domain data calculated on a coarse grid (left) into data with suppressed numerical dispersion (right). The number of channels (depth) in the respective layers is indicated at the bottom under the layer blocks.

with a parameter), with a negative slope factor of 0.2. The PyTorch library is utilized for software implementation.

We use pre-calculated seismograms of a common source point on a fine grid to train the neural network, paired with their "distorted" versions modeled on a coarse grid. Seismograms at the input and output of NDM-net are recorded on the free surface. The seismogram is converted into a tensor of dimensions 512×512x2 to form the input data, where 512 corresponds to the number of frequencies, 512 corresponds to the number of receivers, and 2 corresponds to the real and imaginary parts of the FFT. The entire dataset is divided into a training set and a validation set in proportion 80% and 20%, respectively.

3 Numerical Experiment

All numerical experiments will be carried out using the realistic BP velocity model (Fig. 3). The left-hand side of the model is constructed using a geological cross-section that runs through the Western Gulf of Mexico. In the central part of the model, simplified representations of geological characteristics in the Eastern/Central Gulf of Mexico and off-shore Angola are depicted. The right-hand side of the model is a combination of representations of velocity challenges encountered in regions such as the Caspian Sea, North Sea, or Trinidad. This model is frequently used as a benchmark for prestack depth migration, especially reverse time migration.

The model extends 67.4 km horizontally and 11.9 km in vertical directions. The acquisition geometry consists of 2696 sources spaced equidistantly on the water surface with a step of 25m. For each source, we generate a synthetic seismogram recorded by 512 receivers, maximum source-receiver offset is 6.4

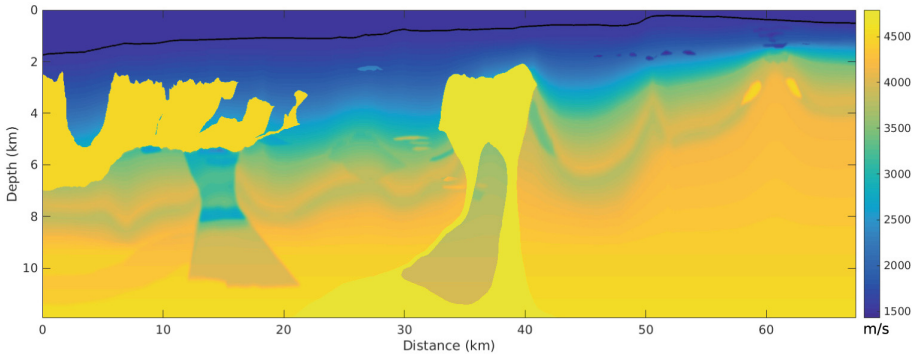

Fig. 3. BP velocity model. The black curve on the top of the model indicates the water bottom (first reflection surface).

km. The source signature is a Ricker wavelet with a peak frequency of 30Hz. We used a 4th-order finite-difference solver with absorbing boundary conditions at all model sides for modeling. We calculated the fine and coarse grid solutions on numerical grids with grid steps 3m and 6m, respectively.

3.1 Generating Training Dataset

As previously stated, we plan to handle seismic data in the frequency domain to process the complete seismogram at once without dividing it in the time domain. Using the characteristics of the BP velocity model (see the black curve in Fig. 3), we conduct an additional transformation in the time domain to align the primary water bottom reflection time across all source positions. As the velocity in the water remains constant in the model, any alterations in velocity begin beneath the water's bottom. This enables us to compute the double vertical time from the source to the corresponding water's bottom location and shift the synthetic seismogram accordingly.

Various approaches were studied in the time domain for performing the NDM-net training (references). In this work, we used 10% of the entire datasets for training, i.e., each 10th source position was used. After performing a time-shift transform, we perform FFT and obtain a training dataset in the frequency domain.

3.2 NDM-Net Training

The training was executed on a single GPU node equipped with dual RTX3090. The root mean square error was selected as the loss function, and we used the Adam optimizer ([8]) with an initial learning rate of 0.0002. During the training, we conducted 50 epochs, which took approximately 45 minutes. The corresponding training curves can be seen in Fig. 4. Subsequently, we employed the NDM-net weights acquired after the 47th epoch to conduct numerical dispersion

suppression on the entire dataset, which was calculated on a coarse grid. The prediction outcomes for a random seismogram from a testing dataset can be viewed in Fig. 5 and 6. Notably, a significant reduction in numerical dispersion is observed following NDM-net post-processing.

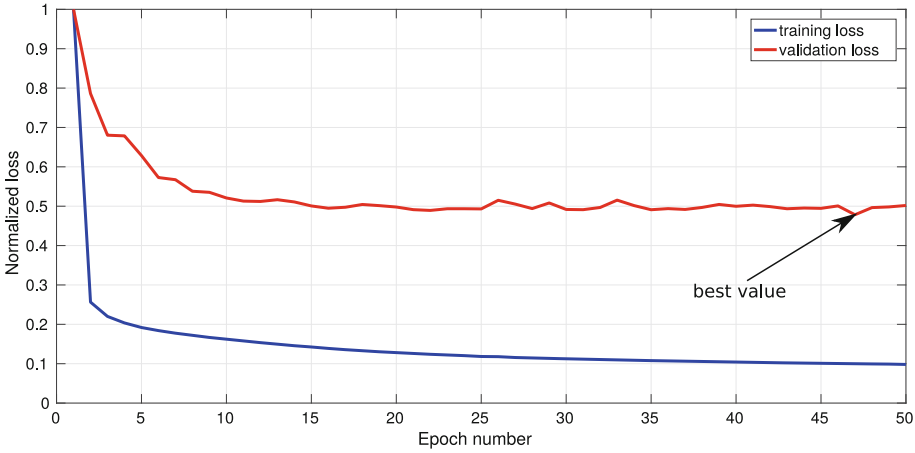

Fig. 4. The training (blue) and validation (red) losses are plotted in a normalized form. The black arrow indicates the best validation prediction results point (epoch number 47). (Color figure online)

3.3 Analyzing Numerical Results

In this study, we calculated the relative error between the fine and coarse grid solution or its NDM-net correction as a percentage using the following formula:

$$error_{relative}(A_i, B_i) = \frac{norm(A_i - B_i)}{norm(B_i)} \times 100\%, \tag{1}$$

here, A_i represents the coarse grid solution for a source with index i, B_i represents the corresponding fine grid solution, and $norm$ represents the Euclidean norm. The Euclidean norm is a commonly used metric to measure the error between two vectors. In this case, we used it to calculate the relative error between the solutions. The resulting error plot, which shows the level of numerical dispersion caused by rough finite difference approximation in dependence on the source position, is shown in Fig. 7 as a red plot. The plot indicates a significant level of numerical dispersion in the coarse grid solution, as evidenced by the high relative error.

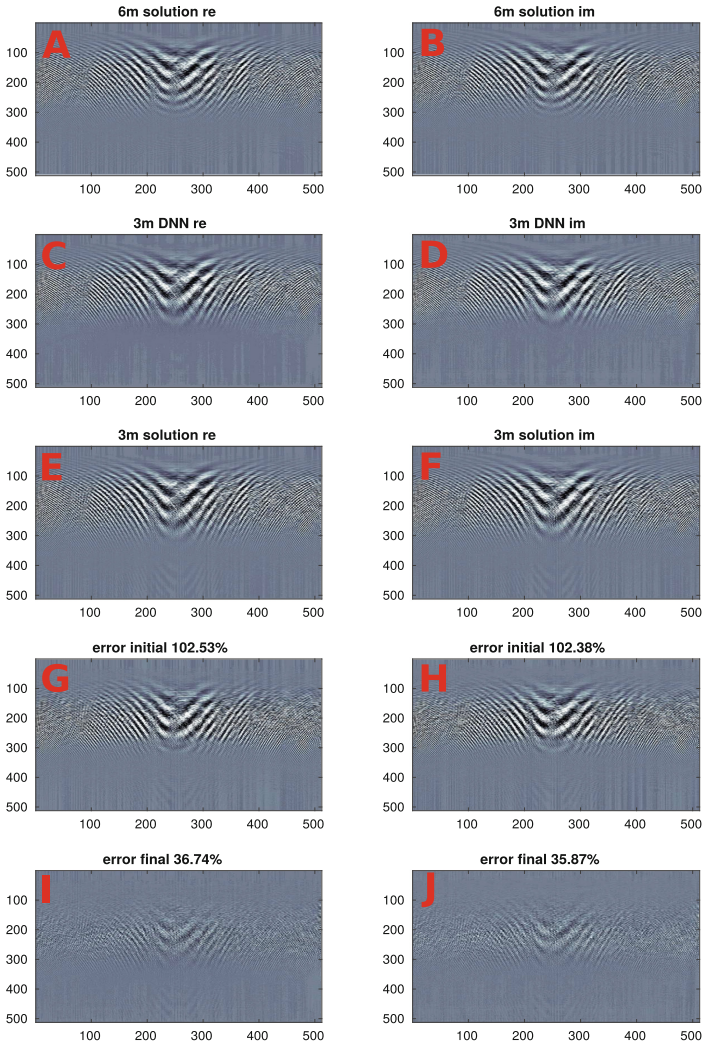

Fig. 5. The NDM-net prediction results for a source located at X=3.2 km. The left column is real parts, and the rights column is imaginary parts of the solution calculated on a coarse grid (A, B) and fine grid (E, F), NDM-net prediction results (C, D), the original dispersion (G, H) and the suppressed dispersion after NDM-net post-processing (I, J).

After performing the NDM-net post-processing and reducing the numerical dispersion in the data, we were able to construct the same relative error curve between the NDM-net predicted data and the fine grid solution. The NDM-net predicted error is plotted as a blue curve in Fig. 7, with a mean value of 31.49%

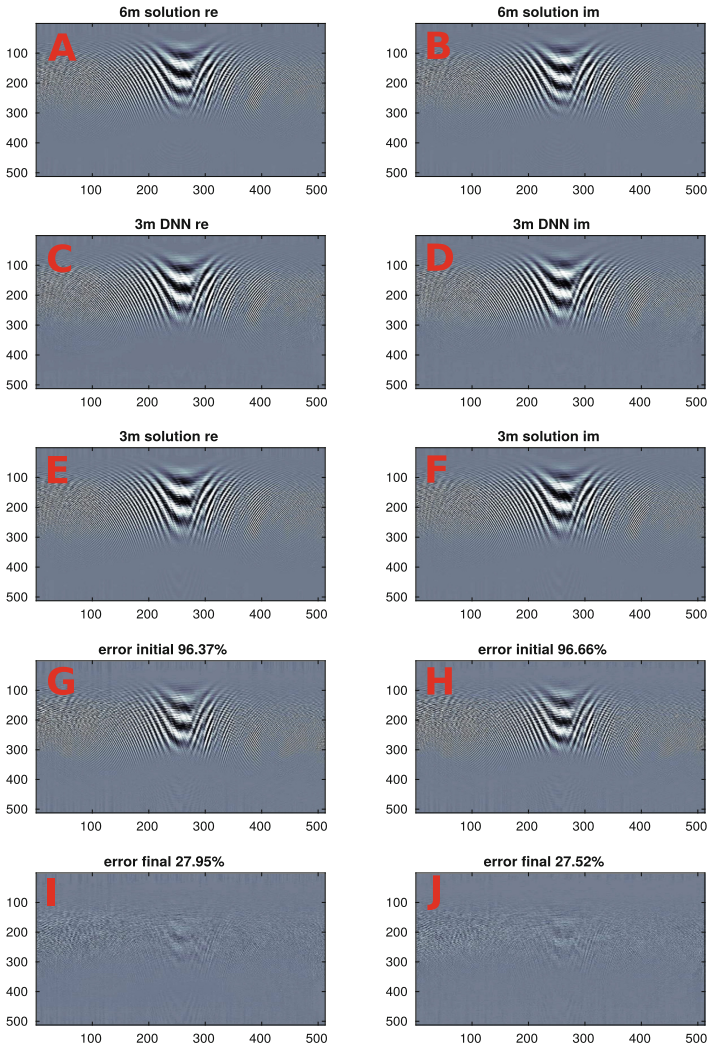

Fig. 6. The NDM-net prediction results for a source located at X=40.7 km. The left column is real parts, and the rights column is imaginary parts of the solution calculated on a coarse grid (A, B) and fine grid (E, F), NDM-net prediction results (C, D), the original dispersion (G, H) and the suppressed dispersion after NDM-net post-processing (I, J).

and a standard deviation of 7.13%. Therefore, we conclude that the level of numerical dispersion decreased three times after applying the NDM-net post-processing.

To better compare the coarse grid and the NDM-net predicted data, we selected two random source indexes from the testing dataset that the NDM-net did not use during training. Figs. 8 and 9 present the conversion of the frequency domain seismograms back to the time domain for these sources. Following Parseval's identity, which states that the Euclidean norm of the FFT seismogram is equal to its norm in the time domain, we observe a similar numerical dispersion level in the time domain.

We also provided trace-by-trace time domain/frequency domain comparisons for better visibility. These comparisons show that the NDM-net predicted and fine grid solutions have a good correlation in both the frequency and time domains, see Fig. 8F and Fig. 9F. The red plot represents the 6m solution, the black plot represents the 3m solution, and the blue plot represents the NDM-net prediction. We can observe a good correspondence between the seismic trace calculated on the fine grid and the NDM-net predictions, indicating the effectiveness of the NDM-net post-processing in reducing the level of numerical dispersion.

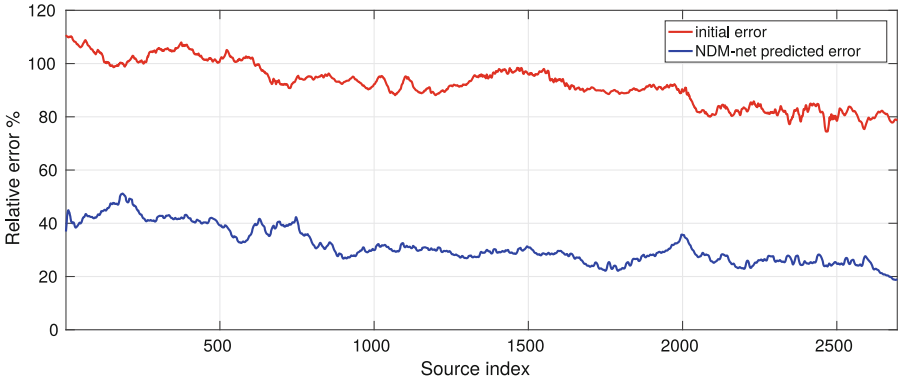

Fig. 7. The relative error between seismogram calculated on a coarse grid and fine grid solution (red plot), and the relative error between NDM-net post-processed seismogram and fine grid solution (blue plot). (Color figure online)

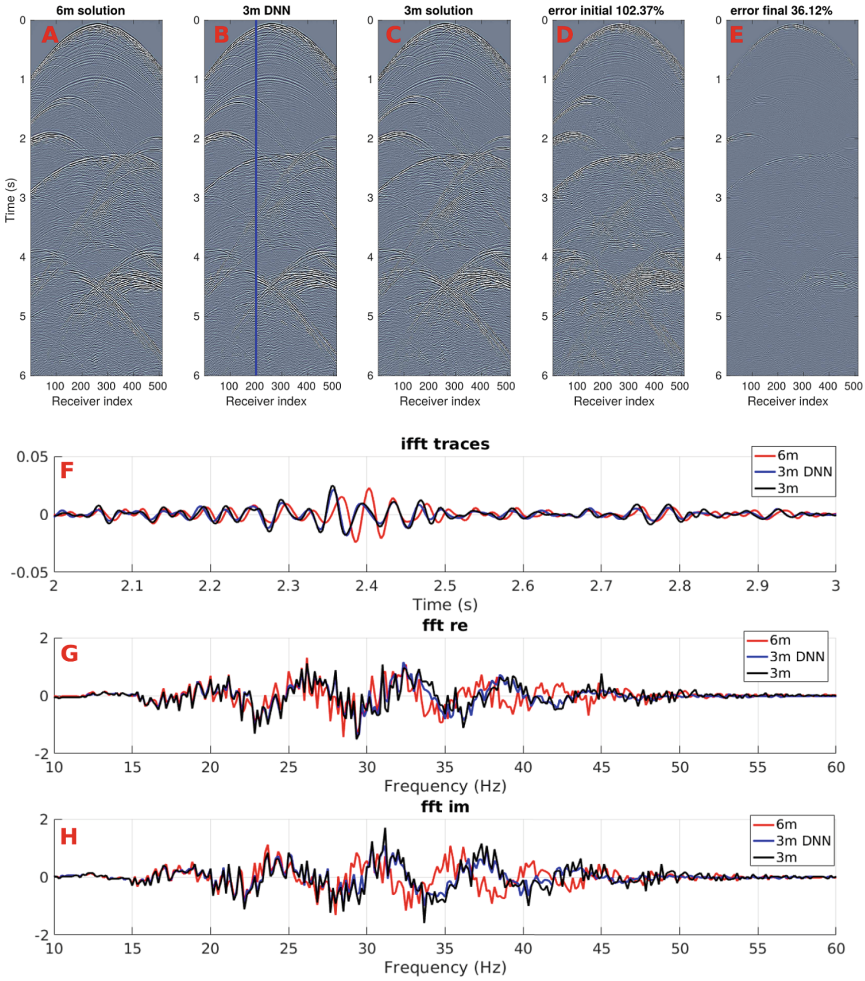

Fig. 8. The NDM-net prediction results for a source located at X=3.2 km converted back from frequency to the time domain. The seismogram modeled on coarse (A) and fine grid (C), the initial numerical dispersion (D) (difference between (C) and (A)), the NDM-net post-processed seismogram (B), and the suppressed numerical dispersion (E) (difference between (C) and (B)). The comparison of traces in the time (F) (trace index 200, see a blue line at (B)) and the frequency domain: real (G) and imaginary parts (H), respectively. Red plot - 6m solution, black plot - 3m solution, and blue plot - NDM-net prediction. (Color figure online)

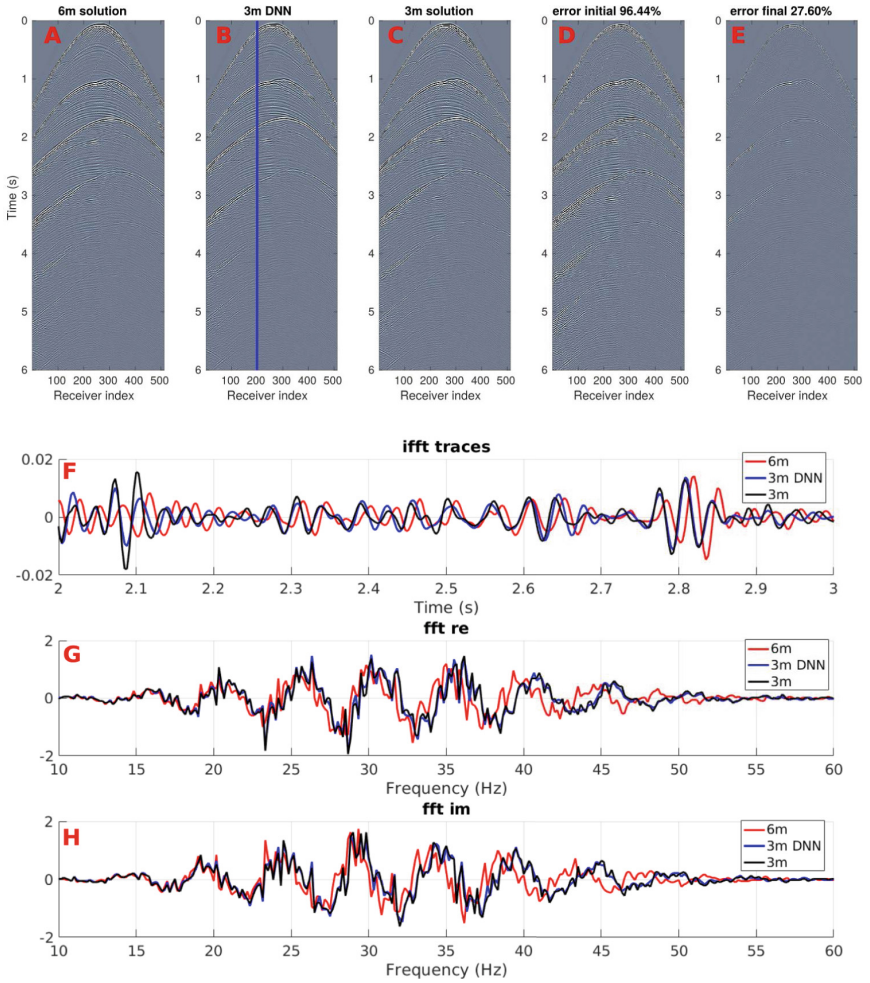

Fig. 9. The NDM-net prediction results for a source located at X=40.7 km converted back from frequency to the time domain. The seismogram modeled on coarse (A) and fine grid (C), the initial numerical dispersion (D) (difference between (C) and (A)), the NDM-net post-processed seismogram (B), and the suppressed numerical dispersion (E) (difference between (C) and (B)). The comparison of traces in the time (F) (trace index 200, see a blue line at (B)) and the frequency domain: real (G) and imaginary parts (H), respectively. Red plot - 6m solution, black plot - 3m solution, and blue plot - NDM-net prediction. (Color figure online)

4 Conclusions

In this study, we proposed using an NDM-net in the frequency domain to mitigate numerical dispersion in seismic data. Unlike time-domain processing, frequency-domain processing offers several advantages, including more efficient

extraction of information from large datasets, noise removal, and correction for amplitude and phase distortions. This approach can significantly enhance the exploration and characterization of hydrocarbon reservoirs, with Full Waveform Inversion (FWI) as a prominent example. We applied our proposed method to a realistic synthetic BP numerical example, which resulted in an average reduction of numerical dispersion by a factor of three and an order-of-magnitude increase in calculation performance. Our approach enabled us to process the entire seismogram simultaneously, in contrast to the time-domain NDM-net implementation. As a result, we can now apply this approach to 3D seismic modeling. Overall, using NDM-net in the frequency domain can significantly improve the quality and efficiency of seismic data processing. This approach could enhance our understanding of hydrocarbon reservoirs and facilitate more accurate exploration and characterization of subsurface structures.

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Field-Split Iterative Solver for Quasi-Static Biot Equation

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Abstract. Frequency domain Biot equation in quasi-static state can be applied to model low-frequency loading of fluid-filled poroelastic materials and estimate effective frequency-dependent strain-stress relations. We propose an algorithm of solving the system of linear algebraic equations (SLAE) obtained from finite-difference approximation of Biot equations. The algorithm involves the Biconjugate Gradient Stabilized (BICGSTAB) iterative solver with a field-split preconditioner technique. In this paper, we estimate the number of floating-point operations required for both the proposed algorithm and direct approach. Performed numerical experiments demonstrate the fast convergence of the iterative process and confirm performance and memory usage benefits of the suggested approach compared to the direct method.

Keywords: Poroelasticity · wave-induced fluid flow · Biot equation · quasi-static state · finite differences · direct methods for SLAE · iterative methods · field-split preconditioner

1 Introduction

Numerical solution of the system of linear algebraic equations (SLAE) problem arises from a differential problem, and often involves computational cost problem, so it requires both knowledge base in mathematical algorithms for solving such systems and program implementation for high-performance computing systems (HPC). Biot equation in the quasi-static state in the frequency domain is approximated by finite-difference approach [10,11] on the staggered grid with partial separation of variables and equations [1]. The SLAE can be solved either by optimised implementation of the direct approach based on LU-decomposition [2,5,9] or by iterative algorithms using preconditioner techniques [14]. There are

S.S. developed the algorithm and M.N. did the numerical simulations using the supercomputer facilities of Siberian Supercomputer Center (Cluster NKS-30T) under the support of RSCF grant no. 19-77-20004. V.L. performed the analysis of the results under the support of FNI project FWZZ-2022-0022.

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various preconditioner approaches such as ILU0, multigrid [13], filed-split [6], etc. In this paper we use the field split preconditioner to separate equations and variables into two groups: related to solid deformation and related to fluid transport, and these equations can be solved separately.

First, we present the numerical upscaling algorithm for estimation of the effective properties of fractured porous isotropic media in the low-frequency range. Then we describe the finite-difference approximation of Biot equations and corresponding mesh stencils, which define the SLAE properties and so effect the details of algorithm of its numerical solution. Two approaches are considered: *Direct* is based on optimised LU matrix decomposition (we use black-box implementation of well known software) and *Iterative* preconditioned solver. We have developed our own matrix preconditioner based on the field-split idea. Floating point operations (FLOPS) estimates for both approaches coupled with memory usage and numerical experiments show the advantages of the direct approach for small problems and the iterative one for the large models.

2 Statement of the Problem

2.1 Biot Equations in Quasi-Static State

In this paper we consider Biot model equations stated in the quasi-static regime representing the pressure diffusion process in fluid-filled poroelastic media [4]:

$$\frac{\partial}{\partial x}\left[C_{11}\frac{\partial u_x}{\partial x}+C_{13}\frac{\partial u_z}{\partial z}\right]+\frac{\partial}{\partial z}\left[C_{55}\left(\frac{\partial u_x}{\partial z}+\frac{\partial u_z}{\partial x}\right)\right]+\frac{\partial}{\partial x}\left[\alpha M\left(\frac{\partial w_x}{\partial x}+\frac{\partial w_z}{\partial z}\right)\right]=0, \tag{1}$$

$$\frac{\partial}{\partial x}\left[C_{55}\left(\frac{\partial u_x}{\partial z}+\frac{\partial u_z}{\partial x}\right)\right]+\frac{\partial}{\partial z}\left[C_{13}\frac{\partial u_x}{\partial x}+C_{33}\frac{\partial u_z}{\partial z}\right]+\frac{\partial}{\partial z}\left[\alpha M\left(\frac{\partial w_x}{\partial x}+\frac{\partial w_z}{\partial z}\right)\right]=0, \tag{2}$$

$$\frac{\partial}{\partial x}\left[\alpha M\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_z}{\partial z}\right)\right]+\frac{\partial}{\partial x}\left[M\left(\frac{\partial w_x}{\partial x}+\frac{\partial w_z}{\partial z}\right)\right]-i\omega\frac{\eta}{k}w_x=0, \tag{3}$$

$$\frac{\partial}{\partial z}\left[\alpha M\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_z}{\partial z}\right)\right]+\frac{\partial}{\partial z}\left[M\left(\frac{\partial w_x}{\partial x}+\frac{\partial w_z}{\partial z}\right)\right]-i\omega\frac{\eta}{k}w_z=0. \tag{4}$$

In these notations $\boldsymbol{u}=(u_x,u_z)^T$ is the velocity vector, $\boldsymbol{w}=(w_x,w_z)^T$ is the relative fluid velocity vector, ω is the time frequency, C_{11}, C_{33}, C_{13}, C_{55} are the components of the fluid-saturated matrix stiffness tensor, M is the fluid storage coefficient, and α is the Biot-Willis coefficient. Note, that the stiffness tensor is the fourth-order tensor, however, due to its symmetry as well as the symmetry of the strain and stress tensors, we can use the Voight notations and write down the Hooke's law in the following form:

$$\begin{pmatrix}\sigma_{xx}\\ \sigma_{zz}\\ \sigma_{xz}\end{pmatrix}=\begin{pmatrix}C_{11} & C_{13} & 0\\ C_{13} & C_{33} & 0\\ 0 & 0 & C_{55}\end{pmatrix}\begin{pmatrix}\varepsilon_{xx}\\ \varepsilon_{zz}\\ \varepsilon_{xz}\end{pmatrix},$$

where the components of the strain tensor are defined as follows:

$$\varepsilon_{xx} = \frac{\partial u_x}{\partial x}, \varepsilon_{zz} = \frac{\partial u_z}{\partial z}, \varepsilon_{xz} = \frac{1}{2}\left(\frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z}\right) \tag{5}$$

The system of Eqs. (1)–(4) should satisfy the following boundary conditions:

$$\begin{aligned} \sigma \cdot \boldsymbol{n}|_{\partial D} &= \boldsymbol{\sigma}_0 \\ \boldsymbol{w} \cdot \boldsymbol{n}|_{\partial D} &= 0. \end{aligned} \tag{6}$$

The goal of this research is to recover the frequency-dependent stiffness tensor, corresponding to orthotropic viscoelastic media so that the solution of the original problem (1)–(4) and (6) coincides with the solution of the upscaled problem:

$$\frac{\partial}{\partial x}\left[\hat{C}_{11}(\omega)\frac{\partial \hat{u}_x}{\partial x} + \hat{C}_{13}(\omega)\frac{\partial \hat{u}_z}{\partial z}\right] + \frac{\partial}{\partial z}\left[\hat{C}_{55}(\omega)\left(\frac{\partial \hat{u}_x}{\partial z} + \frac{\partial \hat{u}_z}{\partial x}\right)\right] = 0, \tag{7}$$

$$\frac{\partial}{\partial x}\left[\hat{C}_{55}(\omega)\left(\frac{\partial \hat{u}_x}{\partial z} + \frac{\partial \hat{u}_z}{\partial x}\right)\right] + \frac{\partial}{\partial z}\left[\hat{C}_{13}(\omega)\frac{\partial \hat{u}_x}{\partial x} + \hat{C}_{33}(\omega)\frac{\partial \hat{u}_z}{\partial z}\right] = 0, \tag{8}$$

$$\hat{\sigma} \cdot \boldsymbol{n}|_{\partial D} = \boldsymbol{\sigma}_0 \tag{9}$$

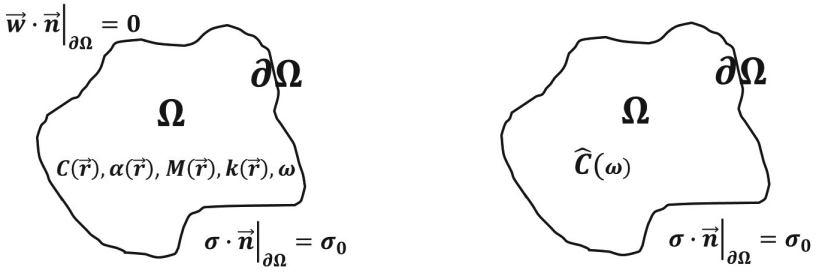

Fig. 1. Left: original fluid-saturated poroelastic media; right: reconstructed effective frequency-dependent viscoelastic media. Vector $\boldsymbol{n}$ is the outer normal, and $C(\boldsymbol{r}), \alpha(\boldsymbol{r}), M(\boldsymbol{r}), k((\boldsymbol{r}))$ are the space-dependent parameters of Eqs. (1)–(4).

To solve the upscaling problem we consider system of equations stated in a rectangular domain $D = [L_1^x, L_2^x] \times [L_1^z, L_2^z]$ with boundary conditions

$$\begin{aligned} (\sigma_{xx}, \sigma_{xz})^t|_{x=L_1^x, x=L_2^x} &= (\sigma_{01}, \sigma_{02})^t = (\phi_x, \psi) \\ (\sigma_{xz}, \sigma_{zz})^t|_{z=L_1^z, z=L_2^z} &= (\sigma_{01}, \sigma_{02})^t = (\psi, \phi_z), \end{aligned} \tag{10}$$

where ϕ_x and ϕ_z are the loads σ_{xx} and σ_{zz} at the opposite sides of the domain, respectively, and ψ is the torsion value applied to all four sides of the domain.

Resolving the problem (1)–(4) one can define the averaged stress and strain components as $\int_\Omega \varepsilon dv = \int_\Omega \hat{\varepsilon} dv = I_\varepsilon$ ($\varepsilon \in \{\varepsilon_{xx}, \varepsilon_{zz}, \varepsilon_{xz}\}$) and same stress σ_0 at the boundary $\partial\Omega$. The strains ε distributions in the original medium satisfy the solution of the Eqs. (1)–(4) with boundary conditions (Fig. 1, left). Thus for $\sigma \in \{\sigma_{xx}, \sigma_{zz}, \sigma_{xz}\}$ (components of the stress tensor in porous fluid-saturated media) $\int_\Omega \sigma dv = \int_\Omega \hat{\sigma} dv = I_\sigma$.

If the upscaled problem (7), (8) is considered in a rectangular domain with the boundary conditions (9) the following relations are valid due to constant values of the stiffness tensor:

$$I_\sigma = \int_\Omega \hat{\sigma} dv = \int_\Omega \hat{C}\hat{\varepsilon} dv = \hat{C} \int_\Omega \hat{\varepsilon} dv = \hat{C} I_\varepsilon$$

If we require the averaged stresses and strains for the two problems to coincide, we finish up with the following system of linear algebraic equations (SLAE) $I_\sigma = \hat{C} I_\varepsilon$ with three equations and nine unknown components of the tensor $\hat{C}$:

$$\begin{aligned} I_{\sigma xx} &= \hat{C}_{11} I_{\varepsilon xx} + \hat{C}_{13} I_{\varepsilon zz} + \hat{C}_{15} I_{\varepsilon xz}, \\ I_{\sigma zz} &= \hat{C}_{31} I_{\varepsilon xx} + \hat{C}_{33} I_{\varepsilon zz} + \hat{C}_{35} I_{\varepsilon xz}, \\ I_{\sigma xz} &= \hat{C}_{51} I_{\varepsilon xx} + \hat{C}_{53} I_{\varepsilon zz} + \hat{C}_{55} I_{\varepsilon xz}. \end{aligned} \tag{11}$$

It is necessary to perform three experiments to obtain a unique solution, because one experiment with one load leads to three Eqs. (11) with nine unknowns $\hat{C}$. Experiments of original media reconstruction use three sets of boundary conditions (10) with basic loads:

– x-direction compression:

$$\phi_x = 1, \phi_z = 0, \psi = 0, \tag{12}$$

– z-direction compression:

$$\phi_x = 0, \phi_z = 1, \psi = 0, \tag{13}$$

– xz-torsion:

$$\phi_x = 0, \phi_z = 0, \psi = 1. \tag{14}$$

The details of the reconstruction of the effective viscoelastic media using set of numerical experiments on different models, estimation of both velocity and quality factors are presented in the paper [12].

Below we briefly describe the discretisation of 2D Biot Eqs. (1)–(4) with the presented boundary conditions (10) and construction of the SLAE. After that we develop algorithms of the numerical solution of this linear system.

2.2 Discretisation of Biot Equations

Biot Eqs. (1)–(4) have been discretised by the rectangular grid of $N_x \times N_z$ points. The domain boundaries cross the mesh cells at the centres of the cell faces as illustrated in Fig. 2.

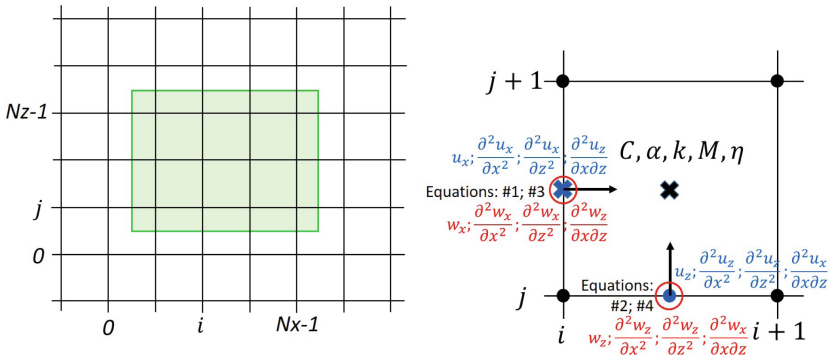

Fig. 2. Discretisation of the computational domain (left). Solution components, derivatives, location of physical parameters on the computational grid, and nodes where equations are approximated (right).

Positions of the variables on the grid are given in the Fig. 2. Horizontal components of the displacement vectors u_x and w_x are defined in the half-integer points in the x direction and at integer points in the z direction. The vertical components of the solution vector are stored at integer points in the x direction and at half-integer points in the z direction. All the coefficients of the equations are defined in integer grid points in both spatial directions. Equations (1) and (3) are approximated at the centres of the vertical edges, (2) and (4) at the centres of the horizontal edges.

Biot equations are approximated inside the computational domain (Fig. 2) and at its boundary. Thus the total number of finite-difference equations approximating the Eqs. (1) and (3) is $(N_x - 1)N_z$; and the number of equations approximating (2) and (4) is $N_x(N_z - 1)$. So, the total number of linear equations is

$$N = 2(N_x - 1)N_z + 2N_x(N_z - 1) \approx 4N_x N_z.$$

Details of the finite-difference approximation of the Biot equations are presented in [12] and will not be discussed here. However, we need to point out the main properties of the derived system of equations. First, the matrix of the system A is a sparse square matrix, which is complex, non-Hermitian and non-symmetric. Second, due to the Neumann-type boundary conditions (6) the matrix is ill-conditioned (singular). In addition, we need to consider the number of non-zero elements $NNZ(A)$ in the matrix A which depends on the finite-difference rules used to approximate the equations. The stencils used to approximate Biot's equations are shown in the Fig. (3). The approximation of the Eqs. (1) and (2) requires 16 points, so it involves 16 elements. The approximation of the Eqs. (3) and (4) requires 14 elements. So, $NNZ(A) \approx 2(16 + 14)N_x N_z = 60N_x N_z$.

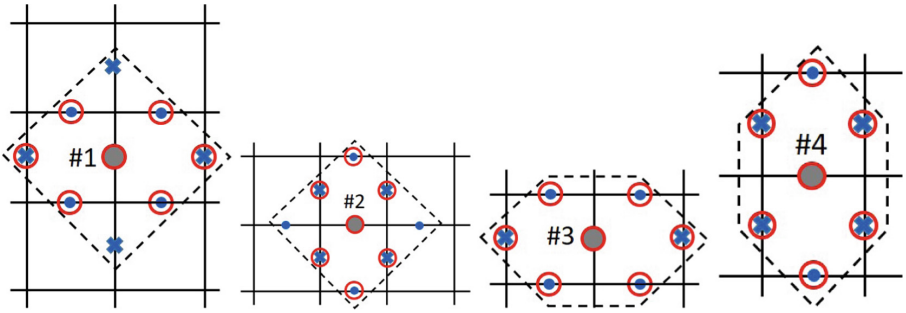

Fig. 3. Patterns for Biot equations.

3 Numerical Solution of SLAE

When developing a solver of SLAE which is derived from the discretisation of differential equations, the following points need to be considered:

- **Accuracy**, which means that the algorithm should provide a reasonable numerical solution error or relative residual.
- **Performance**, which means that the algorithm should solve the SLAE in a reasonable time. Therefore, the number of floating point operations (FLOP) must be estimated and minimised if possible. In addition, the implementation of the algorithm should use the high-performance features like parallelisation.
- **Memory usage** should be minimised if possible, to fit available computational resources.

There are two main groups of methods to solve SLAE: *Direct* methods and *Iterative* methods. Below we consider both approaches and apply them to the solution of Biot equations in the quasi-static state.

3.1 Direct Solver

Direct solvers are based on the LU factorization algorithms. They provide the best achievable accuracy, but require enormous amounts of computer memory and number of flops. For sparse SLAEs, there are special algorithms that reduce memory consumption and flops. These algorithms include reordering of columns and rows of the initial matrix, multifrontal factorization, and others. They are implemented in commercial solvers such as SuperLU [9], MUMPS [2], PARDISO[5], etc. In our previous research we proposed an algorithm to solve the Biot equations in the quasi-static state using the direct solvers [12]. However, due to severe memory limitations (512 Gb of RAM), the use of the direct solver did not allow us to proceed to problems with more than 2000^2 points.

For the sake of completeness we recall the main estimates of the RAM $Mem(Dir)$ and Flops $Flops(Dir)$ to solve the Biot equations using the direct solver.

Sparse direct solver performs three steps to solve SLAE:

1. Reordering (preliminary step to reduce the number of non-zeros in the LU factors),
2. Factorization (perform LU factorization),
3. Solving (solve the systems $Ly = b$ and $Ux = y$).

The Reordering uses graph partitioning algorithms to permute the columns and rows of initial matrix before factorization. It operates with integer numbers, faster than factorization step and can be executed just once for all time frequencies. The last is due to the fixed matrix pattern which is independent of the frequency. We do not take this step into account to estimate $Flops(Dir)$. Factorization and solving steps are performed for every frequency. Thus,

$Flops(Dir) = N_{freq}[Flops(Fct) + Flops(Slv)]$.

The number of flops at solving step $Flops(Slv)$ can be estimated by the number of non-zero elements in L and U, because a single element in these matrices leads to two operations (one summation and one multiplication). The matrix A is structurally symmetric (not self-adjoint), so the patterns of L and U coincide, and $NNZ(LU) = 2 * NNZ(L)$. We also need to consider the number of right hand sides (RHS). Three different loads provide three RHS, so $Flops(Slv) = (3\ RHS) * (2\ operation\ per\ one\ element) * (2NNZ(L))$

Finally, the total number of floating-point operations is:

$Flops(Dir) = N_{freq}[Flops(Fct) + 12NNZ(L)]$.

Below we provide the values of $Flops(Fct)$ and $NNZ(L)$ corresponding to the particular experimental set-up.

3.2 Iterative Solver

Iterative algorithms mostly use less memory than direct methods. However, the accuracy of the solution is not guaranteed if convergence of iterative process is poor. Different preconditioners are used to speed up the convergence rate [3,7,8,13]. The preconditioner B leads to the SLAE: $\hat{A}x = \hat{b}$ where $\hat{A} = B^{-1}Ax$, $\hat{b} = B^{-1}b$. To solve the complex non-hermitian matrix $\hat{A}$ the BICGSTAB algorithm [14] is used:

$$
\begin{aligned}
&set\ x_0\\
&set\ j_{restart}\\
&r_0 := \hat{b} - \hat{A}x_0\\
&p_0 := r_0\\
&For\ j = 0, 1, \ldots, until\ convergence\ Do:\\
&a_j := \tfrac{(r_j, r_0^*)}{(\hat{A}p_j, r_0^*)}\\
&s_j := r_j - a_j\hat{A}p_j\\
&\omega_j := \tfrac{(\hat{A}s_j, s_j)}{(\hat{A}s_j, \hat{A}s_j)}\\
&x_{j+1} := x_j + \alpha_j p_j + \omega_j s_j\\
&r_{j+1} := s_j + \omega_j \hat{A}s_j\\
&If\ remainder(j/j_{restart}) = 0\ Then\ r_{j+1} := \hat{b} - \hat{A}x_{j+1}\\
&\beta_j := \tfrac{(r_{j+1}, r_0^*)}{(r_j, r_0^*)}\tfrac{\alpha_j}{\omega_j}\\
&p_{j+1} := r_{j+1} + \beta_j(p_j - \omega_j\hat{A}p_j)\\
&EndDo
\end{aligned}
\tag{15}
$$

To compute the number of floating-point operations of BCGStab we should count the "constant times a vector plus a vector" operations (**axpy**), the scalar product (**dot**) and the $\hat{A}x$ product (the most time consuming part of this algorithm). The $\hat{A}x$ product consists of the matrix-vector product of the initial matrix A (**mv**) and the inversion the preconditioner B (**inv**). Taking into account the Flops provided in the Table 1 the total number of operations for iterative process can be estimated as:

$Flops(Itr) = N_{freq}N_{iter}[80N + 2Flops(invB)]$.

The construction of the preconditioner B and the counting $Flops(invB)$ is described in the next subsection.

Table 1. Estimation of floating-point operations number for the major operations in BCGStab. We suppose that $N = 4n^2$ and $NNZ(A) = (32 + 26) * n^2 = 15N$.

Operation type	Nflops per one operation	Number of operations per one step
axpy	2N	6
dot	2N-1	4
mv	2*NNZ(A)	2
inv	TBD	2

3.3 Construction of the Preconditioner

On the one hand the preconditioner B should be easily invertible, on the other hand it should not be as close to the inverse matrix of the system as possible. The standard preconditioners like Jacoby, Zeidel, Block-Jacoby are not suitable

for Biot equations in the quasi-static state. According to numerical experiments they do not guarantee the convergence of the BCGStab.

Another approach to construct preconditioner B is called "Field-Split" [6]. The idea is to reduce the system of equations to the block-lower-triangular form; i.e., to exclude the variable w from the Eqs. 1, 2. Then the equilibrium equations for the elastic matrix can be solved, and its solution can be used to construct a right-hand side of the Eqs. 3, 4. Then the components of w can be found as the solution of the Eqs. 3, 4 with new right-hand sides (Table 2).

So, the matrix representation of the preconditioning operator can be represented as:

Table 2. Differential equation of "Field-Split" preconditioner B.

$\frac{\partial}{\partial x}\left[C_{11}\frac{\partial u_x}{\partial x}+C_{13}\frac{\partial u_z}{\partial z}\right]+\frac{\partial}{\partial z}\left[C_{55}\left(\frac{\partial u_x}{\partial z}+\frac{\partial u_z}{\partial x}\right)\right]$	$+0$		$=0$
$\frac{\partial}{\partial x}\left[C_{55}\left(\frac{\partial u_x}{\partial z}+\frac{\partial u_z}{\partial x}\right)\right]+\frac{\partial}{\partial z}\left[C_{13}\frac{\partial u_x}{\partial x}+C_{33}\frac{\partial u_z}{\partial z}\right]$	$+0$		$=0$
$\frac{\partial}{\partial x}\left[\alpha M\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_z}{\partial z}\right)\right]$	$+\frac{\partial}{\partial x}\left[M\left(\frac{\partial w_x}{\partial x}+\frac{\partial w_z}{\partial z}\right)\right]$	$-i\omega\frac{\eta}{k}w_x$	$=0$
$\frac{\partial}{\partial z}\left[\alpha M\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_z}{\partial z}\right)\right]$	$+\frac{\partial}{\partial z}\left[M\left(\frac{\partial w_x}{\partial x}+\frac{\partial w_z}{\partial z}\right)\right]$	$-i\omega\frac{\eta}{k}w_z$	$=0,$

Table 3. Block representation of the initial matrix A, low-triangular preconditioner B, vectors x and y.

$$\mathrm{A}=\begin{array}{|c|c|}\hline A_0 & A_1\\ \hline A_2 & A_3\\ \hline\end{array}\quad \mathrm{B}=\begin{array}{|c|c|}\hline A_0 & 0\\ \hline A_2 & A_3\\ \hline\end{array}\quad \mathrm{x}=\begin{array}{|c|}\hline x_0\\ \hline x_3\\ \hline\end{array}\quad \mathrm{y}=\begin{array}{|c|}\hline y_0\\ \hline y_3\\ \hline\end{array}$$

Therefore the algorithm of the solution SLAE $Bx = y$ is:

1. Solve $A_0 x_0 = y_0$
2. Set $y_3 = y_3 - A_2 x_0$
3. Solve $A_3 x_3 = y_3$

Note that the matrices A_0 and A_2 are real and do not depend on the frequencies ω. The matrix A_3 has complex values only on the main diagonal. Pattern of these matrices and corresponding differential operators are presented in the Fig. (4) and Table (4).

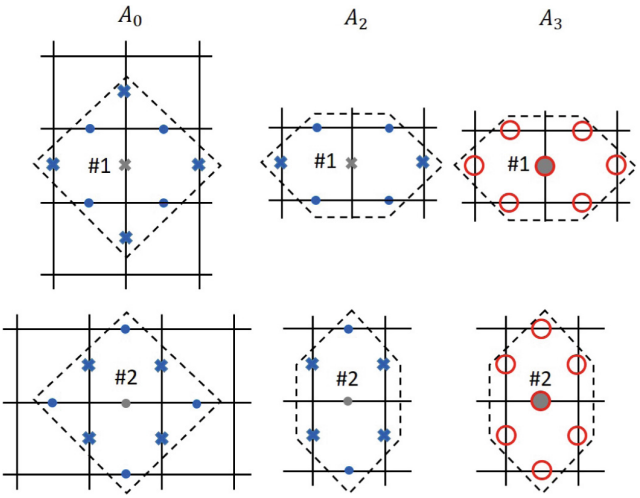

Fig. 4. Left: pattern for equation A_0; Center: pattern for equation A_2; Right: pattern for equation A_3;

Table 4. Differential equation of the "Field-Split" preconditioner B.

A_j block of B	Differential operator	number of A_j non-zeros
A_0	$\frac{\partial}{\partial x}\left[C_{11}\frac{\partial u_x}{\partial x}+C_{13}\frac{\partial u_z}{\partial z}\right]+\frac{\partial}{\partial z}\left[C_{55}\left(\frac{\partial u_x}{\partial z}+\frac{\partial u_z}{\partial x}\right)\right]$ $\frac{\partial}{\partial x}\left[C_{55}\left(\frac{\partial u_x}{\partial z}+\frac{\partial u_z}{\partial x}\right)\right]+\frac{\partial}{\partial z}\left[C_{13}\frac{\partial u_x}{\partial x}+C_{33}\frac{\partial u_z}{\partial z}\right]$	$2*9*n^2$
A_2	$\frac{\partial}{\partial x}\left[\alpha M\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_z}{\partial z}\right)\right]$ $\frac{\partial}{\partial z}\left[\alpha M\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_z}{\partial z}\right)\right]$	$2*7*n^2$
A_3	$\frac{\partial}{\partial x}\left[M\left(\frac{\partial w_x}{\partial x}+\frac{\partial w_z}{\partial z}\right)\right]-i\omega\frac{\eta}{k}w_x$ $\frac{\partial}{\partial z}\left[M\left(\frac{\partial w_x}{\partial x}+\frac{\partial w_z}{\partial z}\right)\right]-i\omega\frac{\eta}{k}w_z$	$2*7*n^2$

Let us now estimate the flops to invert the preconditioner: $Flops(invB) = Flops(invA_0) + 14n^2 + Flops(invA_3)$. The main benefit of inversion A_0 and A_3 compared to inversion of the full matrix A is that A_0 and A_3 are smaller than A, and A_0 does not depend on frequency and can be factorized only once in the case of inversion by direct solvers. The A_3 should be factorized for each frequency. Thus, the following estimation is valid:

$$Flops(invB) = [Flops(FctA_0)+Flops(SlvL_0)]+14n^2+[Flops(FctA_3)+Flops(SlvL_3)]$$

.

Estimates of $Flops(SlvL_0)$ and $Flops(SlvL_3)$ can be obtained from the number of non-zero elements of the factors L_0 and L_3: $Flops(SlvL) = 12Nnz(L)$. So, the total number of floating-point operations is:

$$Flops(Itr) = Flops(FctA_0)+$$
$$+N_{freq}[Flops(FctA_3) + N_{iter}[80N + 2 * 12Nnz(L_0) + 14n^2 + 2 * 12Nnz(L_3)]]$$

4 Numerical Experiments

As mentioned in the previous sections, the time taken by the solvers depends heavily on the number of floating-point operations. Additional functionality such as the approximation of Biot equation and the construction of the effective stiffness tensor C do not require high number of FLOPS, but can also affect the performance. The approximation requires a lot of data coping which makes this part of the algorithm "bandwidth-limited" and difficult to speed up. This operation is optimised by constructing the matrix one time for all frequencies ω_i and modifying only the diagonal for each ω_i. The construction of the stiffness tensor C is performed for each frequency, but it handles with small number of operations. The numerical experiments confirm the small time of execution of the mentioned functions in comparison with the numerical solution of SLAE. Moreover, we estimate parameters for counting FLOPS for both direct and iterative approaches (Table 3).

We considered Biot equations stated in a square domain. The model corresponds to the fractured porous media, as presented in Fig. (5). The coefficients of the Biot equations in fractures and in the background are provided in Table (5).

Table 5. Coefficients of Biot equations for numerical experiments.

Coeff	Background	Crack
C_{11}	$69.10 * 10^9$	$38.96 * 10^9$
C_{12}	$7.159 * 10^9$	$32.67 * 10^9$
C_{22}	$69.10 * 10^9$	$38.96 * 10^9$
C_{33}	$30.97 * 10^9$	$22.62 * 10^9$
M	$20.10 * 10^9$	$9.330 * 10^9$
αM	$5.953 * 10^9$	$6.854 * 10^9$
$\frac{\eta}{k}$	$1000 * 10^9$	$0.007 * 10^9$

Let us recall the estimates of the flops for the two approaches:

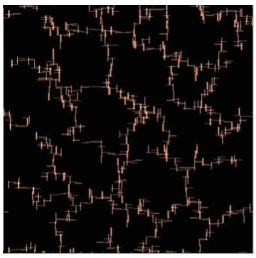

Fig. 5. Model crack.

- Direct solver: $Flops(Dir) = N_{freq}[Flops(FctA) + 12 * NNZ(L)]$,
- Iterative solver: $Flops(Itr) = Flops(FctA_0) + N_{freq}[Flops(FctA_3) + N_{iter}[80N + 2 * 12Nnz(L_0) + 14n^2 + 2 * 12Nnz(L_3)]]$.

Number of FLOPS for factorization and number of non-zero elements for various SLAE sizes N (various Biot mesh sizes n) are provided in the Table 6. The stopping criterion of BCGStab is based on achieving the relative residual $\|\hat{b} - \hat{A}x_0\|/\|\hat{b}\| < 10^{-10}$. It is enough to compute the effective tensor $\hat{C}$.

Table 6. Results of numerical experiments: Number of FLOPS, number of non-zero elements in L-factors and number of iterations.

Mesh size	$\hat{A}$ size	FLOPS number			Non-zero number*10^9			Iteration number
$n = n_x = n_z$	N	$FctA$	$FctA_0$	$FctA_3$	L	L_0	L_3	N_iter
250	$0.25 * 10^6$	67	13	3	0, 024	0, 007	0, 004	4
500	$1 * 10^6$	655	137	36	0, 116	0, 035	0, 019	4
1000	$4 * 10^6$	5312	1241	304	0, 539	0, 170	0, 091	4
2000	$16 * 10^6$	45119	11178	3445	2, 477	0, 770	0, 434	4
4000	$64 * 10^6$	N/A	93872	28881	N/A	3, 711	1, 965	4

First of all, we need to point out that BCGStab converged in only 4 iterations when using the field-split preconditioner. Number of flops to factorize the matrix A_0 is four times less than to factorize the entire matrix A. Factorization of the matrix A_3 requires even smaller number of flops and it is about 5% of that for the matrix A. Moreover, using the direct solver does not allow solving the problem of the size of 4000^2 points, while the iterative solver is suitable for such a problem. However, to estimate the total number of the flops for the iterative solver, we need to take into account the number of iterations to achieve the appropriate accuracy. Also, the necessity to solve Biot equations for a series of frequencies should also be considered. The number of floating-point operations estimation (for 30 frequencies) is shown in the Table 7. In general, the BCGStab iterative

solver with split-field preconditioner requires only 10% of the flops needed to solve the Biot equation with the direct solver.

Table 7. Total number of FLOPS for 30 frequencies.

Mesh	GFLOPS	
$n = n_x = n_z$	Direct	Iterative
250	2029	149
500	19690	1372
1000	159554	11159
2000	1354471	118158
4000	N/A	977291

5 Conclusion

We presented an iterative solver to solve the discretized Biot equation in quasi-static state. The solver is based on the BCGStab algorithms with field-split preconditioner. The idea of the approach is to use the block lower-triangular matrix as the preconditioner of the entire system. To invert the preconditioner, it is necessary to solve the static elastic equations and the Darcy equations (with respect to relative fluid displacements) independently. Solving the two independent problems is much simpler, than solving the coupled problem and requires fewer number of flops and less memory (RAM). In this research we used the direct solvers to invert the parts of the preconditioner, and compared the performance of the proposed algorithm with a purely direct solver of the entire system. We showed that the use of BCGStab reduces the computation time by the factor of ten compared to the direct solver. Indeed, using of the direct solver to invert the diagonal blocks of the preconditioner may not be the optimal choice, and our further research will focus on constructing appropriate iterative processes to deal with the preconditioner.

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Seismic Monitoring of Hydrocarbon Deposits Using a Viscoelastic Medium Model Based on Deep Learning

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Abstract. This paper presents a novel approach to solving the inverse dynamic seismic problem in seismic monitoring for the viscoelastic medium. The proposed method offers a cost-effective alternative to Full Waveform Inversion by using a deep convolutional neural network Unet-type architecture with residual blocks to approximate an inverse problem operator that translates the change in seismic data into the change in velocity models. The operability of the proposed approach is demonstrated through a model example under the assumption that the distribution of the velocity model is known at the initial moment. Furthermore, the results of neural network prediction on a realistic sample with Gullfaks deposit indicate the practical applications of the proposed approach in seismic monitoring. The proposed approach shows significant potential for advancing the state-of-the-art in solving the inverse dynamic seismic problem for the viscoelastic medium, with potential implications for improving seismic monitoring techniques in industry and academia.

Keywords: Viscoelastic medium · full waveform inversion · deep learning · seismic monitoring

1 Introduction

Building a reliable model of the Earth is a prerequisite for the search for oil and gas deposits, mining, and other geophysical tasks. The solution of the inverse dynamical problem is the primary tool in seismic exploration to obtain a high-resolution model of the Earth's internal geological structure. One of the most critical recoverable parameters in the study of coal reservoir hydrocarbons is the velocity and the corresponding attenuation of seismic wave energy since it characterizes the rock's fluid saturation. Thus, knowledge of the spatial distribution of attenuation noticeably increases the reliability of the interpretation of the results of seismic observations

Recently, the Full waveform Inversion (FWI) [9] method has become a reliable and high-resolution method for constructing geological parameters with complex

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structures from the results of measuring wave fields on the surface. It was first proposed in a series of papers by Guy Chavent and Albert Tarantola [2,8] in the time domain based on the generalized least squares method. Frequency domain FWI [6] has been developed to speed up the inversion. However, FWI has several significant disadvantages:

- the ill-posedness of the inverse problem manifests itself in the non-uniqueness of the solution and the instability when using noisy data in the inversion.
- strong non-linearity of the objective functional, which leads to the convergence of the method to a local minimum.
- sensitivity of the solution to the presence of low-frequency information in seismic data.
- the presence of elastic parameters coupling when solving a multi-parameter inverse problem, which leads to the incorrect reconstruction of the parameters.
- high computational cost mainly manifested in the restoration of the elastic parameters of the medium in a three-dimensional formulation. Substantial computational resources are required to calculate the wave fields in solving the inverse problem at each iteration of the nonlinear least squares method.

Thus, an efficient and robust FWI technique is needed for optimal oil field development. Motivated by the remarkable achievements of neural networks as non-linear approximators in computer vision, deep learning presents itself as a promising methodology for FWI as an alternative to conventional modeling approaches. The learning-based strategy obviates the need for explicit problem modeling and offers the significant benefit of economizing on computational resources expended on seismic data processing. In the proposed method, the computational expenditures are primarily incurred during the initial stages, comprising the generation of a representative training dataset and training the neural network. At subsequent stages, the trained neural network replaces the processing, enabling it to forecast the petrophysical characteristics of the reservoir by leveraging seismic data at various developmental stages.

This research paper presents a novel approach for resolving a complex multi-parameter inverse dynamic seismic problem for a viscoelastic medium model. The proposed solution involves utilizing deep learning elements to reconstruct the model of velocities (V_p) and quality factors (Q_p) of longitudinal waves. Specifically, the method involves training a deep convolutional neural network (CNN) of the ResUnet architecture to approximate the nonlinear inverse problem operator F^{-1}. This operator is responsible for establishing the link between the computed waveforms and the velocity model of the medium. By leveraging the power of deep learning techniques, our approach demonstrates significant potential for tackling this challenging problem.

2 Theory and Method

2.1 Seismic Wave Propagation Modeling for a Viscoelastic Medium Model

Let us examine a two-dimensional model of a viscoelastic medium, wherein seismic waves manifest as mechanical vibrations of the rock resulting from an excitation source. The absorption of seismic energy, which is an inherent feature of all natural geological settings, is quantified by a quality factor:

$$Q^{-1} = \frac{1}{2\pi}\frac{\Delta E}{E}, \tag{1}$$

here, we denote E as the seismic energy per unit volume per unit time, and ΔE as its corresponding loss per unit volume per unit time. In this context, the propagation of seismic waves within a viscoelastic medium can be modeled by the following set of equations in the frequency domain:

$$\begin{cases} i\omega\rho\mathbf{u} = \mathrm{div}\sigma + \mathbf{f}, \\ i\omega\varepsilon = \dfrac{1}{2}(\nabla\mathbf{u} + \nabla\mathbf{u}^*), \\ \sigma_{ij} = \left(\lambda\left(1 + \dfrac{i}{Q_p}\right) + 2i\mu\left(\dfrac{1}{Q_p} - \dfrac{1}{Q_s}\right)\right)\mathrm{tr}\,\varepsilon\delta_{ij} + 2\mu\left(1 + \dfrac{i}{Q_s}\right)\varepsilon_{ij}, \end{cases} \tag{2}$$

where the displacement velocity is represented by $\mathbf{u} = (u, v)^T$, while the strain and stress tensors are denoted by ε and σ, respectively. Additionally, ρ stands for density, λ and μ denote the Lamme coefficients, and Q_p and Q_s correspond to the quality factors of longitudinal and transverse waves, respectively. These quality factors are used to describe the absorption of longitudinal and transverse waves. Furthermore, ω signifies frequency, and the source of seismic waves is given by $\mathbf{f} = (f, g)^T$.

The first equation in the aforementioned set is responsible for capturing the dynamics of a continuous medium and expresses the law of conservation of momentum. The second equation introduces the linear Cauchy-Green strain tensor, which quantifies the relationship between the strain tensor and the corresponding displacement velocities. Finally, the third equation is Hooke's law for an isotropic medium, which specifies the relationship between the various components of the stress tensor and the corresponding strain tensor.

Having expressed the components of the stress tensor in terms of the displacement velocities and substituting them into the equation of motion, we obtain the relation for the displacement velocities:

$$\begin{cases} \omega^2\rho u + \dfrac{\partial}{\partial x}\left[\left(\lambda\left(1+\dfrac{i}{Q_p}\right)+2i\mu\left(\dfrac{1}{Q_p}-\dfrac{1}{Q_s}\right)\right)\left(\dfrac{\partial u}{\partial x}+\dfrac{\partial v}{\partial z}\right)+2\mu\left(1+\dfrac{i}{Q_s}\right)\dfrac{\partial u}{\partial x}\right]+ \\ \qquad +\dfrac{\partial}{\partial z}\left[\mu\left(1+\dfrac{i}{Q_s}\right)\left(\dfrac{\partial u}{\partial z}+\dfrac{\partial v}{\partial x}\right)\right]=f, \\ \omega^2\rho v + \dfrac{\partial}{\partial z}\left[\left(\lambda\left(1+\dfrac{i}{Q_p}\right)+2i\mu\left(\dfrac{1}{Q_p}-\dfrac{1}{Q_s}\right)\right)\left(\dfrac{\partial u}{\partial x}+\dfrac{\partial v}{\partial z}\right)+2\mu\left(1+\dfrac{i}{Q_s}\right)\dfrac{\partial v}{\partial z}\right]+ \\ \qquad +\dfrac{\partial}{\partial x}\left[\mu\left(1+\dfrac{i}{Q_s}\right)\left(\dfrac{\partial u}{\partial z}+\dfrac{\partial v}{\partial x}\right)\right]=g. \end{cases} \tag{3}$$

Absorbing boundary conditions of the PML (Perfectly Matched Layers) type [10] are used as boundary conditions. Then the partial derivative operators $\dfrac{\partial}{\partial x}$, $\dfrac{\partial}{\partial z}$ of the (3) system inside the absorbing layer are replaced by the operators $\dfrac{\partial}{\partial \tilde{x}}$, $\dfrac{\partial}{\partial \tilde{z}}$:

$$\begin{gathered} \frac{\partial}{\partial \tilde{x}} = \frac{1}{1+\frac{d_x(x)}{i\omega}}\frac{\partial}{\partial x}, \qquad \frac{\partial}{\partial \tilde{z}} = \frac{1}{1+\frac{d_z(z)}{i\omega}}\frac{\partial}{\partial z}, \\ d_x(x) = d_0\left(\frac{l(x)}{L}\right)^4, \qquad d_z(z) = d_0\left(\frac{l(z)}{L}\right)^4, \end{gathered} \tag{4}$$

where L is the width of the absorbing layer, $l(x), l(z)$ is the distance from a point in the absorbing layer to the inner boundary of the region.

To numerically solve the (3) system, we use a finite-difference approximation of partial derivatives, in conjunction with an unconditionally stable fourth-order implicit scheme. The grid for this scheme is depicted in Fig. (??). After discretizing the (3) system, we obtain a system of algebraic equations which we solve using LU decomposition. Furthermore, the Ricker wavelet serves as the source function for our calculations.

2.2 Inverse Seismic Dynamic Problem

We will now define an inverse dynamic seismic problem aimed at restoring the parameters of a viscoelastic medium model. To achieve this, we introduce the model of a viscoelastic medium, denoted by $m = (\rho, \lambda, \mu, Q_p, Q_s)^T$. Subsequently, we can define the direct problem operator $\mathcal{F}_s(m, \omega_j) : M \to U$. This operator associates the m models for a fixed time-frequency with the solution of the (3) system of equations. Here, the source takes the form of $\delta(\mathbf{x}-\mathbf{x_s})\mathbf{f}(\omega)$, with $\delta(\mathbf{x}-\mathbf{x_s})$ representing the Dirac delta function. It is noteworthy that the result of this operator actually corresponds to the product of the momentum shape $\mathbf{f}(\omega)$ and the Green's function $G(\mathbf{x_s}, \mathbf{x}, \omega, m)$ of the given system.

Let us introduce into consideration a linear operator for taking the trace of a full wave field from one of the sources at a fixed time frequency at points corresponding to the location of geophones:

$$P : U \to \mathbb{C}^{Nr}, \tag{5}$$

where Nr is the number of receivers. Then the wave field recorded by receivers on the surface for a fixed source s and a fixed frequency ω_j can be represented as a superposition of operators:

$$F_s^j = P \circ \mathcal{F}_s(m, \omega_j) : M \to \mathbb{C}^{Nr}. \tag{6}$$

If only Ns sources are used, then the data space for each of them at a fixed frequency ω_j is determined by the action of the following operator:

$$F^j(m) = \begin{pmatrix} F_1^j(m) \\ \vdots \\ F_{Ns}^j(m) \end{pmatrix} : M \to \mathbb{C}^{Nr \times Ns} \tag{7}$$

Finally, we obtain the following forward modeling operator from the model space to the data space:

$$F(m) = \begin{pmatrix} F^1(m) \\ \vdots \\ F^{Nf}(m) \end{pmatrix} : M \to D \tag{8}$$

where $D = \mathbb{C}^{Nr \times Ns \times Nf}$, Nf - number of time-frequencies used during the inversion.

Thus, the inverse problem is to determine the model of the medium from the wave field recorded in the coordinates of the receivers so that the nonlinear identity is satisfied

$$d_{obs} = F(m), \tag{9}$$

where $d_{obs} = (\dots \mathbf{u}_s(\mathbf{x}_r, \omega_j) \dots)^T \in D, r = 1 \dots Nr, s = 1 \dots Ns, j = 1 \dots Nf$, $\mathbf{x}_r$ – coordinates of the receivers, $\mathbf{u}_s$ – wave field for the source $\delta(\mathbf{x} - \mathbf{x_s})\mathbf{f}(\omega)$, $\mathbf{x}_s$ – source coordinate.

Let us introduce the misfit functional

$$E(m) = \frac{1}{2}\|d_{obs} - F(m)\|_2^2. \tag{10}$$

The standard FWI formulation is to minimize the (10) functional, i.e., finding the model $m^* \in M$

$$m^* = \underset{m}{\operatorname{argmin}}\, E(m). \tag{11}$$

The well-known formula for gradient computation looks as follows

$$\nabla E(m) = -\Re\left(\left(\frac{\delta F}{\delta m}(m)\right)^{*}(d_{obs} - F(m))\right). \tag{12}$$

Most existing methods for solving this problem rely on gradient methods such as conjugate gradients to find the minimum point of the functional. However, this approach demands a significant amount of computational resources as it requires solving the direct problem multiple times during each iteration of minimizing the functional.

2.3 Approximation of the Inverse Problem Operator by a Deep Convolutional Neural Network

Statement of the Problem. Let's examine an alternative approach to solving the inverse problem, which is data-driven. We suppose that we possess a sample that accurately depicts the correlation between the seismic data and the corresponding geological model of the environment. By minimizing the loss function, we can train on the given dataset to retrieve the F^{-1} inverse problem operator:

$$F_{*}^{-1} = \underset{F^{-1}\in U}{\operatorname{argmin}} L(m, F^{-1}(d)), \tag{13}$$

where L is the loss function expressing the discrepancy between the data and the action of the inverse problem operator on the model, U is the space of functions used to approximate the inverse problem operator.

This study will focus on utilizing deep learning methods for full waveform inversion. The inverse problem operator F^{-1} will be approximated using a deep convolutional neural network (CNN). It has been shown in [11] that a deep convolutional neural network can approximate any continuous function of several variables with any predetermined accuracy. However, it is important to note that the theorem guarantees the existence of such an architecture and weights for an artificial neural network. Still, it does not guarantee that the optimization learning process necessarily converges to this point. Thus, if the sample used for training is representative, then seismic data mapping to the environment model can be learned with fairly high accuracy. Since the operator of the direct problem is assumed to be differentiable, the continuity of the operator of the inverse problem follows automatically. After training, the reconstructed operator $\hat{F}^{-1}$ is applied to new seismic data d_{new} to predict the medium model m_{pred}:

$$m_{pred} = \hat{F}^{-1}(d_{new}). \tag{14}$$

The learning-based approach avoids direct modeling of the problem and the construction of the adjoint operator, thereby significantly reducing resource requirements during subsequent stages of applying the inverse operator $\hat{F}^{-1}$. However, the efficacy of this approach is contingent on the availability of a representative training sample and is highly sensitive to its quality.

In our work, we consider the transition to changes in models and seismic data. At t_1, the reservoir model m_1 and the corresponding seismic data d_1 are known to us. At a later time t_2, the velocity model of the reservoir changes slightly to m_2, and the corresponding seismic data changes to d_2. Instead of solving for m_2 given d_2 in the (9) setting, we aim to estimate the change in the model, denoted as $\Delta m = m_2 - m_1$, by the corresponding change in seismic data, denoted as $\Delta d = d_2 - d_1$. Therefore, the original learning task (13) will be replaced with the following task:

$$\mathcal{F}^{-1} = \underset{\mathcal{F}^{-1}}{\operatorname{argmin}} L(\Delta m, \mathcal{F}^{-1}[\Delta d]). \tag{15}$$

Such a transition makes achieving a better approximation of the inverse problem operator possible since it allows restoring more complex geological objects and structures in the environmental model.

Thus, the solution of the inverse dynamic seismic problem is replaced by the task of training a deep convolutional neural network, where the input parameters are the change in seismic data, and the output parameters are the change in the model of the environment.

DNN Architecture. We have chosen a ResUnet convolutional neural network architecture to translate data from seismograms into models. This architecture has been widely used in geophysical applications for various classes of problems, ranging from time-based data processing algorithms to inverse problems. The complete network architecture is shown in Fig. 1. The encoder-decoder structure consists of convolutional blocks that extract high-level features from the input seismic data and compress them into a lower-dimensional multidimensional tensor. The low-dimensional distribution of the data is learned, and then using a decoder consisting of convolutional blocks, the low-dimensional representation of the data is converted into output models. The architecture contains skip connections that pass the information received by the encoder to the decoder, which helps to deal with the problem of gradient decay during the training process. Residual connections (residual units) are also introduced to prevent local gradient fading in convolutional blocks.

Each (16) convolution block consists of a convolution operator Conv, a batch normalization BN [3], and an activation function ReLU [5].

$$\mathbf{x}^{l+1} = \mathrm{ReLU}\left(\mathrm{BN}\left(\mathrm{Conv}\left(\mathbf{x}^{l}\right)\right)\right). \tag{16}$$

The convolution operation presented in equation (17) was initially developed for image processing, utilizing the weight distribution of convolutional kernels to reduce the number of parameters required during training. In our neural network, we utilize a 3×3 convolution kernel, a sliding step size of 1, and a padding value of 1 to preserve the feature map size after each convolution operation.

$$\mathrm{Conv}(\mathbf{x})_{(i,j)} = \sum_{m} \sum_{n} \sum_{c} k_{m,n,c} \cdot \mathbf{x}_{(s-1)\times i+m,(s-1)\times j+n,c}, \tag{17}$$

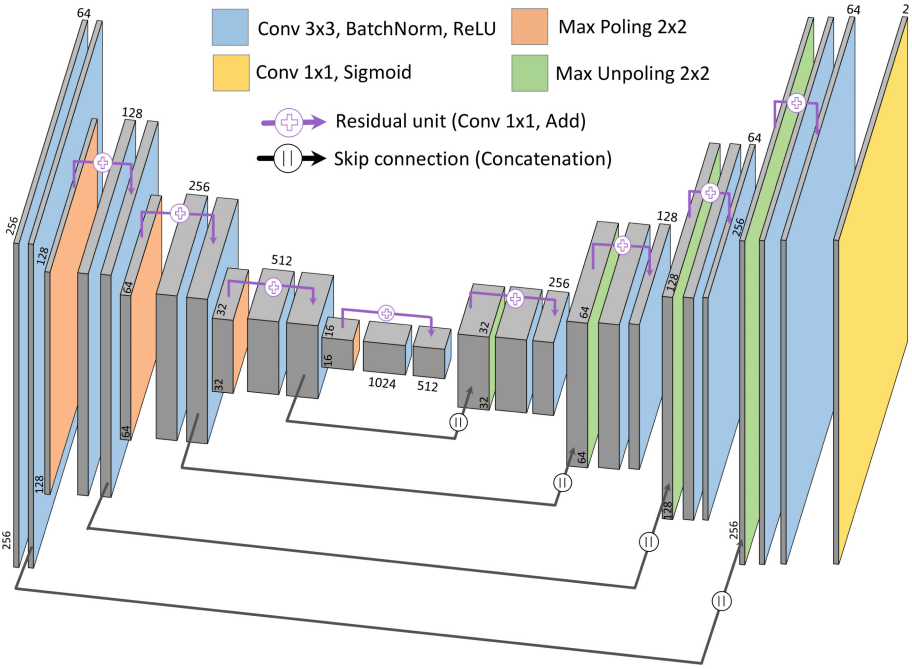

Fig. 1. Block diagram of the ResUnet deep convolutional neural network architecture. Each block represents output feature maps. The number above the block indicates the number of channels. The numbers on the side indicate the size of the feature map. Blue denotes a convolutional block consisting of a convolutional layer with a convolution kernel 3×3, batch normalization, and an activation function ReLU. Orange indicates the aggregation operator maxpooling with a window of 2×2 to reduce the dimension of the feature map. Green indicates the aggregation operator maxunpooling with a window of 2×2 to increase the dimension of the feature map. The purple arrows indicate the residual joins, consisting of a convolution with a kernel of size 1×1 and tensor addition. Black arrows represent skip connections implemented using tensor concatenation. The last layer of the neural network is highlighted in yellow, consisting of a convolution with a 1×1 kernel and an activation function Sigmoid. (Color figure online)

where the input data to the convolution block $\mathbf{x}$ and the trainable kernel of the convolution operator K are three-dimensional tensors with the first two dimensions i, j and m, n responsible for the spatial coordinate, and the third for the number of channels c, s – step with which the convolution kernel runs through the input data.

To regularize the learning process, a layer of batch normalization (2.3) is used, which brings the output of each layer to a distribution with mean β and variance γ, which are also learning parameters.

$$\mathrm{BN}_{\gamma,\beta}\left(\mathbf{x}_{i,j,c}\right) = \gamma\left(\frac{\mathbf{x}_{i,j,c} - \mu_{\mathcal{B}}}{\sqrt{\sigma_{\mathcal{B}}^2 + \varepsilon}}\right) + \beta,$$

where γ and β are two training parameters, $\mu_{\mathcal{B}}$ and $\sigma_{\mathcal{B}}^2$ are the mean and variance, computed for each feature map $\mathbf{x}$ over data packets, ε is a negligible constant introduced for numerical stability of the method.

The activation function ReLU (2.3) is used to introduce non-linearity into the approximation of the inverse problem operator. The main advantage of this activation function is that the derivative does not vanish for positive values of the argument, which again contributes to the fight against gradient decay in the learning process.

$$\mathrm{ReLU}(\mathbf{x}) = \begin{cases} \mathbf{x}, & \text{if} \quad \mathbf{x} \geq 0 \\ 0, & \text{if} \quad \mathbf{x} < 0. \end{cases}$$

In the encoder of our neural network, we use the max pooling aggregation operator to reduce the dimension of the feature map by selecting the maximum values within a given window. Similarly, in the decoder, we use the max unpooling operator after the convolutional blocks to increase the dimension of the feature map by restoring the values in the window of a given size to the location of the maximum value. At the end of the network, we apply a convolution with a 1×1 kernel to adjust the output models to the required size. We use the Sigmoid activation function (18) to constrain the output model values to the interval $[0, 1]$.

$$\mathrm{Sigmoid}(x) = \frac{1}{1 + e^{-x}}. \tag{18}$$

DNN Training. Thus, using the convolutional neural network, the architecture of which is described above, we are looking for the inverse problem operator F^{-1} in the form of a mapping:

$$\begin{aligned} F^{-1} &\approx \hat{F} = f_n\left(\ldots f_2\left(f_1\left(d, w_1\right), w_2\right), \ldots, w_n\right), \\ x_{i+1} &= \begin{cases} f_1\left(d, w_1\right), & i = 1 \\ f_i\left(x_i, w_i\right), & i > 1 \end{cases}, \quad i = 1, \ldots, n \end{aligned} \tag{19}$$

The convolutional neural network in our study is made up of n convolutional blocks, with f_i representing one such block. The network takes as input seismic data d and uses network weights w_i, which are optimized to minimize the loss function. In order to train the network, we select a loss function L and an optimizer that minimizes the loss function (15). We choose to use the root mean square error (20) as our loss function, which is a commonly used metric for regression problems. Additionally, we employ the Adam optimizer [4], which is an adaptive learning rate optimization algorithm that combines momentum accumulation and gradient frequency maintenance principles.

$$L = \frac{1}{N} \sum_{i=1}^{N} \left(m_i^{true} - m_i^{pred} \right)^2, \tag{20}$$

where m_i^{true} is the true model, $m_i^{pred} = \hat{F}(d_i^{obs})$ is the predicted model, N is the size training dataset.

The training process involves updating the weights in (19) using the optimizer in each training epoch. Once the training of the convolutional neural network is complete, it can be used to predict the environmental model. Since the architecture mainly consists of the convolution operator and the activation function ReLU, the predictions can be made very quickly.

The coefficient of determination R^2 was employed to evaluate the training quality accuracy:

$$\begin{aligned} R^2 &= 1 - \frac{\sum_{i=1}^{N} \left(m_i^{true} - m_i^{pred} \right)^2}{\sum_{i=1}^{N} \left(m_i^{true} - \bar{m} \right)^2}, \\ \bar{m} &= \frac{1}{N} \sum_{i=1}^{N} \left(m_i^{true} - m_i^{pred} \right). \end{aligned} \tag{21}$$

Training Dataset. Creating a representative training dataset is an important task when training a CNN. For the purposes of this study, the CNN was trained on a synthetic training set of 2D data. It is important to note that during the creation of the training sample, it was assumed that only the velocity V_p and the quality factor Q_p of longitudinal waves underwent a change in the model. At the same time, the other parameters of the medium remained unchanged. As a result, only changes in the velocities and Q-factor of compressional waves were reconstructed from the corresponding changes in seismic data in this study.

To create a training sample, the Gullfaks [1] field, located in the North Sea, was chosen. The 2D elastic model of this field is shown in Fig. (2). It consists of 559×801 points with a sampling step of 5 m.

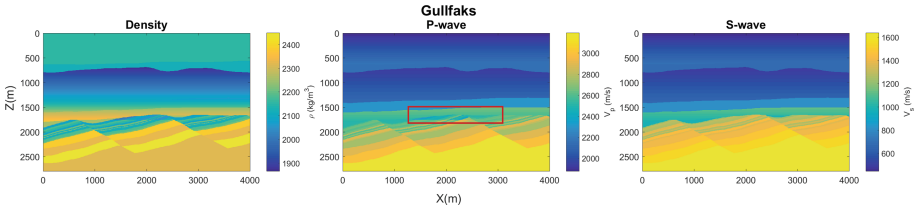

Fig. 2. The figure shows the elastic model of the Gullfaks deposit, with the density model ρ on the left, the velocity model of longitudinal waves V_p in the center, and the velocity model of shear waves V_s on the right. A red rectangle indicates the target area. (Color figure online)

Assuming a viscoelastic model of our medium, we introduced a constant quality factor of longitudinal and transverse waves with a value of 1000, which indicates that there is almost no absorption of both longitudinal and transverse waves. According to the information provided in [7], we have picked a target area containing wells that confirm the presence of oil in these areas. We filled this area with a value of 1500 m m/s for P-wave velocities and 10 for the Q-factor of P-waves, indicating fluid in the toe area. We cut out a part of the model of size $n_z \times n_x$ ($n_z = n_x = 256$) with a sampling step of 10 m so that the target area remains in the model. Thus, we got the reservoir's starting model, shown in Fig. (3).

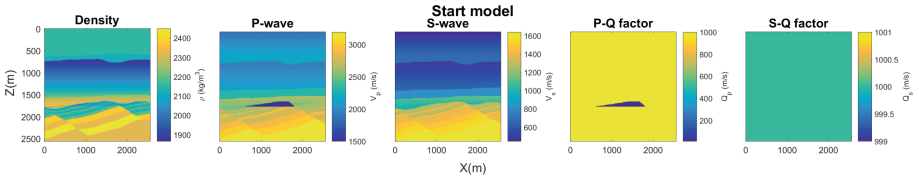

Fig. 3. The starting model of the reservoir used in the training sample. From left to right: there is a model of density ρ, longitudinal velocities V_p, transverse velocities V_s, the quality factor of longitudinal waves Q_p, the quality factor of transverse waves Q_s of the reservoir, respectively.

We assume that the shape of the reservoir changes randomly after the injection of a displacing agent. To achieve this, we vary the shape of the reservoir using a stochastic algorithm. Additionally, we set the velocity of longitudinal waves to 1500 m/s and the quality factor of longitudinal waves to 10, leaving all other parameters unchanged. This generates 1000 different true environment models whose changes we aim to restore. We obtain the changes by subtracting the true starting model and normalizing the model changes to the values of the interval [0,1]. Then, we combine the changes for the velocities and Q-factor of longitudinal waves into a common tensor of dimension $2 \times n_z \times n_x$ to serve as the neural network's output. A few examples of the generated true models and their corresponding changes are shown in Fig. (4).

After generating models, seismic data is modeled using finite difference formulas, as shown in Fig. (??). The approach described in the (??) paragraph is used, and a surface acquisition geometry is employed. At the level $z_s = 0$, $N_s = 256$ sources are evenly distributed with a step of 10 m, $x_s = 10 : 10 : 2550$ m. Similarly, at $z_r = 0$, $N_r = 256$ receivers are evenly distributed with a step of 10 m, $x_r = 10 : 10 : 2550$ m. T15 Hz Ricker wavelet is used as the source, and $N_f = 9$ frequencies with a step 2 Hz, $\omega = 4 : 2 : 20$ Hz are used for modeling seismic data. To accelerate the calculation time for creating a training dataset, the solver is parallelized by frequencies using MPI technology. Only the vertical component of the displacement velocity v is used to register a seismic signal. The data acquisition scheme is shown in Fig. (5). Seismic data is first modeled for a

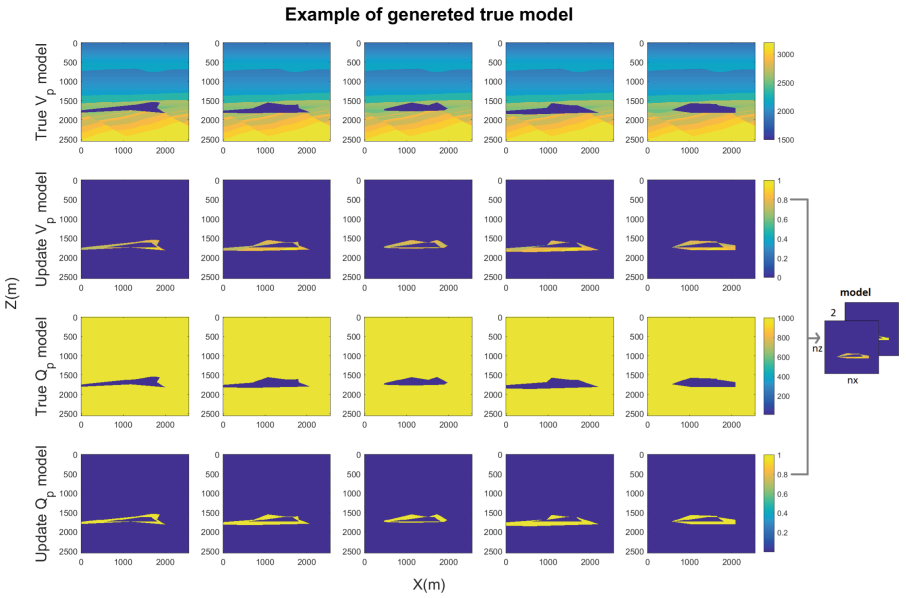

Fig. 4. Examples of generated true reservoir models and their corresponding changes that form the training sample. The first line contains examples of models of longitudinal velocities v_p, and the second line contains the corresponding normalized changes in longitudinal velocities Δv_p. The third line contains examples of models of the quality factor of longitudinal waves Q_p. The fourth line contains the corresponding normalized changes in the quality factor of longitudinal waves ΔQ_p. The arrows show how the change tensor of the $2 \times n_z \times n_x$ ($n_z = n_x = 256$) model is formed, which serves as the output of the neural network.

specific frequency ω_j, and the real and imaginary parts are extracted from them. The data is then converted into $N_s \times N_r$ feature maps for the real and imaginary parts. By subtracting the data for the starting model from the data for the true model, the data corresponding to the change in the model is obtained. The data change is normalized to the values of the interval [0,1] and combined over all frequencies into a tensor of dimension $2N_f \times N_s \times N_r$. This tensor serves as the input of the neural network for training.

In the resulting data set, 70% of the sample is used for the training part, on which we will train the neural network, and 30% for the validation part to ensure that the neural network does not overfit. The division is done so that the distributions of the training and test sets are similar. Separately, several examples are created for the test part, on which the quality of training will be assessed.

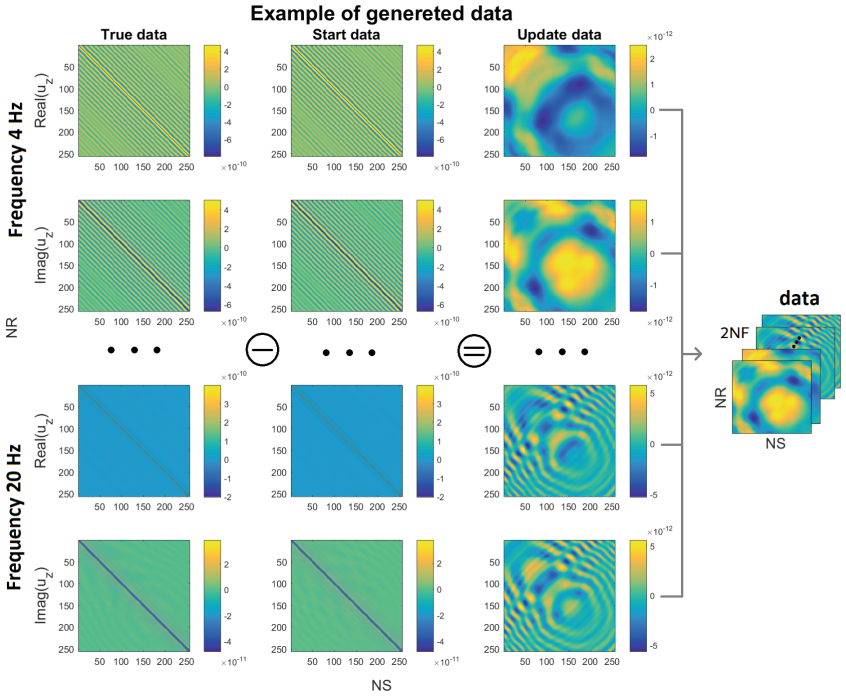

Fig. 5. Examples of simulated synthetic data forming a training set. The data is a feature map of size $N_s \times N_r$, which contains the values of the vertical component of the displacement velocity u_z, recorded by the receiver r on the Earth's surface for the excitation source s. The first column contains the data simulated for the true models, the second column contains the data for the starting model, and the third column contains the data change. The first and second lines contain the real and imaginary parts of the vertical component of the displacement velocity u_z, modeled at a frequency 4 Hz. In the next two lines, similarly for a frequency 6 Hz, and so on up to a frequency 20 Hz. The arrows show how the $2N_f \times N_s \times N_r$ ($N_f = 9, N_s = N_r = 256$) data change tensor is formed, which serves as the input of the neural network.

3 Numerical Experiments

A convolutional neural network (CNN) is typically trained in two stages: the first stage is training, during which the loss function is minimized; the second stage is validation, where we monitor the generalization error. In this case, the ResUnet was trained for 100 epochs, using an initial learning rate of 0.001 and a data batch size of 16. Figure 6 displays the variation in the loss function (20) and the metric (21) on the training and validation sets during the learning process. As the number of epochs increases, we observe a decrease in the loss function on both parts of the data. However, around epoch 60, the learning process no longer reduces the generalization error. Consequently, to assess the quality of training, we fixed a model with weights at epoch 60 on the test set (highlighted by a

dot on the graph). At epoch 60, the loss function for the training and validation parts reached $3 \cdot 10^{-4}$ and 1.72^{-3}, respectively. The prediction accuracy at epoch 60 was 94% for the training set and 89% for the validation set.

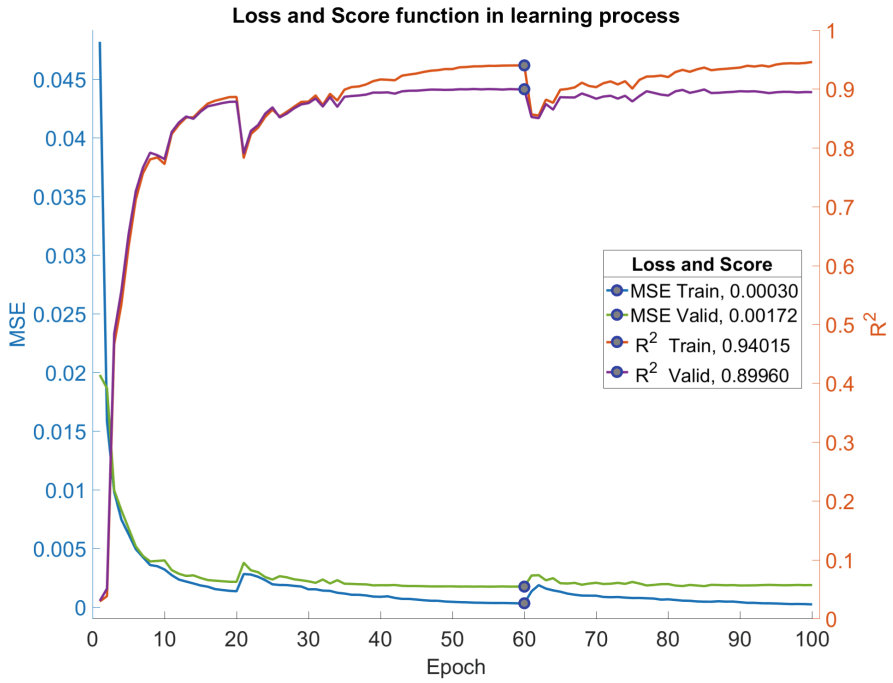

Fig. 6. Changing the MSE loss function and the R^2 metric during neural network training. The left vertical axis corresponds to the MSE values, and the blue and green lines show the change in MSE during training for the training and validation sets, respectively. The right vertical axis corresponds to the values of R^2, and the orange and purple lines show the change in R^2 during training for the training and validation sets, respectively. The point on the graph indicates the moment when the loss function on the validation part of the sample reached its minimum value. The plot legend contains the values of the functions corresponding to the point. (Color figure online)

After training, the neural network was applied to the test dataset. The results of predicting changes in the models of velocities and quality factors of longitudinal waves are shown in Fig. (7 and 8). As one can see, the convolutional neural network generally copes with restoring the environment model from seismic data.

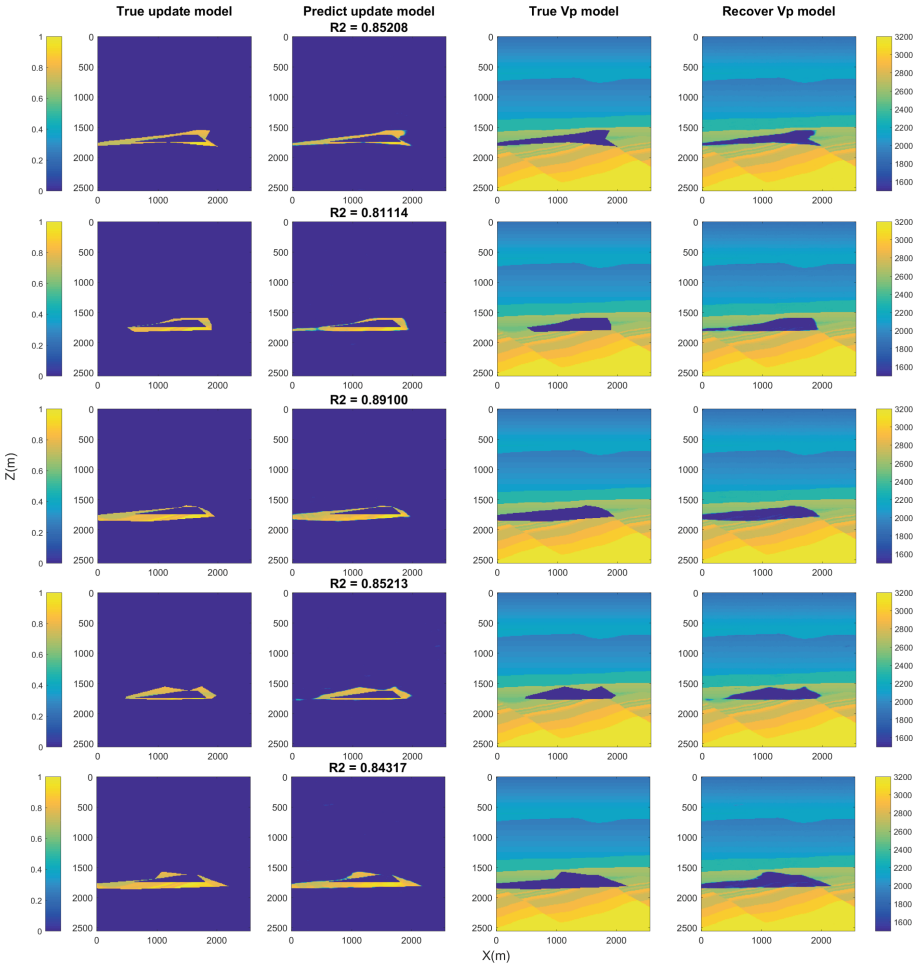

Fig. 7. Examples of predicting changes in the velocity of longitudinal waves by a neural network on a test set. The first column contains the true change in the velocity model. The second column contains the neural network's prediction of the speed model. Above the prediction is the value of the R^2 metric. The third column contains the true velocity model. In the fourth column the reconstructed velocity model for predicting velocity changes.

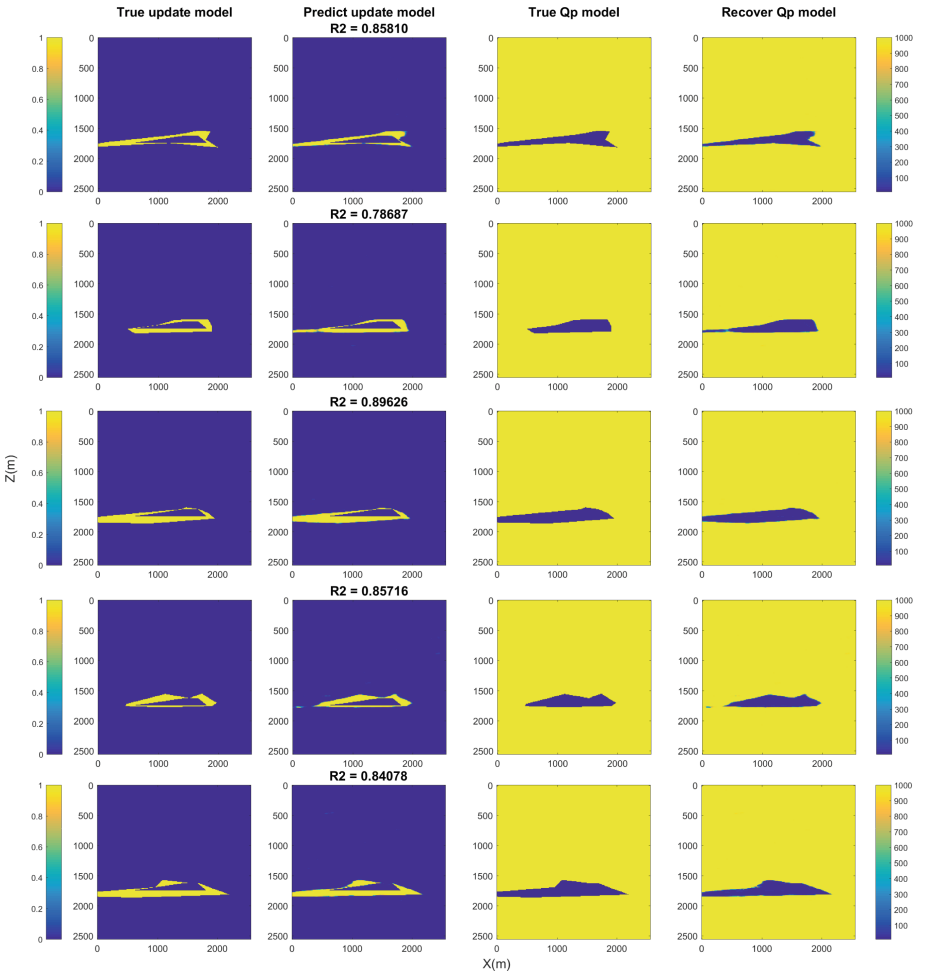

Fig. 8. Examples of predicting changes in the quality factor of longitudinal waves by a neural network on a test sample. The first column contains the true change in the quality factor model. The second column contains the prediction of the quality factor model by the neural network; above the prediction, the value of the R^2 metric is indicated. The third column contains the true quality factor model. In the fourth column, the reconstructed Q-factor model is presented.

4 Conclusions

The paper presents an innovative approach to addressing the inverse dynamic seismic problem in seismic monitoring for the viscoelastic medium. The proposed method offers a cost-effective alternative to Full Waveform Inversion by utilizing a deep convolutional neural network Unet-type architecture with the residual blocks to approximate an inverse problem operator that translates the change in

seismic data into the change in velocity models. The model example presented in this paper demonstrates the operability of this approach for solving the inverse seismic problem under the assumption that the distribution of the velocity model is known at the initial moment. The results of neural network prediction on a realistic sample with Gullfaks deposit indicate that the proposed approach has practical applications in seismic monitoring. Overall, the proposed approach holds significant promise for advancing the state-of-the-art in solving the inverse dynamic seismic problem for the viscoelastic medium, with potential implications for improving seismic monitoring techniques in industry and academia.

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Adaptive Data-Based Optimization of the Training Dataset for the NDM-net

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Abstract. This paper presents a new approach to construct the training dataset for the Numerical Dispersion Mitigation network (NDM-net). The network was designed to suppress numerical error in seismic modeling results. In this approach, a small number of seismograms generated using coarse and fine girds are used to train the network, mapping the inaccurate coarse-grid data to the high-quality fine-grid data. After that, the network is applied to the entire set of seismograms, precomputed using the coarse grid to reduce the numerical error. The most time-consuming part of the suggested approach is the training dataset generation. Thus, we need to minimize the number of seismograms in the training dataset without the loss of the training quality. We suggest constructing the training dataset preserving the Hausdorff distance between the training dataset and the entire dataset. However, the level of the limiting distance may vary depending on the seismogeological model used for simulation. We illustrate that the adaptive strategy is preferred over the fixed Hausdorff distance limiting level because it allows reducing the training dataset without loss of accuracy.

Keywords: Deep learning · seismic modelling · numerical dispersion

1 Introduction

The Numerical Dispersion Mitigation neural network (NDM-net) was suggested recently [3] to suppress numerical error in seismic modeling efficiently. The idea of the approach is to use the deep-learning to post-process the numerically generated seismic wavefields and reduce the numerical dispersion caused by the

Vadim Lisitsa developed the algorithm of optimal dataset construction and Kseniia Gadylshina performed numerical experiments on NDM-net training under the support of RSF grant no. 22-11-00004. Dmitry Vishnevsky performed seismic modeling using NKS-30T cluster of the Siberian Supercomputer Center under the support of basic research project FWZZ-2022-0022. Kirill Gadylshin optimized the NDM-net hyperparameters.

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wavefield under resolution. Seismic modeling requires the numerical solution of acoustic, elastic, anelastic, or poroelastic wave equation [22] with different types of extra complexities, such as free surface topography or rough sea level [10,11,18,20], anisotropy [12,17], fluid intrusions, and karsts. The numerical experiments' design typically compromises the numerical error due to the coarse grid and the extreme time and computational resources consumption due to fine grid usage. In particular, if the finite difference schemes on symmetric stencils are applied [7,21], the numerical error manifests itself as a numerical dispersion, which may destroy the signal. Typically the grid is constructed so that the time delay due to the dispersion in the recorded signal does not exceed one-quarter of the wave period. This condition should be satisfied for the signal traveling 100 to 200 wavelengths. So, the condition is strict, and for typical set-ups may lead to a grid size of as small as one meter. Taking into account the size of the standard domain of interest of 10 by 10 by 5 km, one would finish up with the estimate of $5 \cdot 10^{11}$ grid points to discretize the model, or $6 \cdot 10^{12}$ degrees of freedom to simulate the wavefield in isotropic elastic media. Indeed, modern supercomputers are capable of such simulations. However, this estimate is valid for the wavefield modeling corresponding to a single source, whereas typical acquisition systems contain up to 10^5 shots. Simulation of the entire dataset would require an unacceptably high amount of computational resources. Indeed, there are alternative approaches to seismic modeling, such as finite elements, spectral elements, discontinuous Galerkin [4,11], pseudo-spectral method [15], and others. However, they allow using coarser mesh but with a higher number of degrees of freedom per element, resulting in similar overall estimates of the degrees of freedom and computational intensity to approximate the entire problem [1,9].

There is also a set of approaches based on the post-processing of the simulated data to reduce the numerical error. It includes direct subtraction of the dispersion due to coarse spatial discretization [6,13], which is not capable of reducing dispersion due to discretization of time direction. The other direction of the research is the use of machine learning to resolve this problem, as suggested in [3,5,19]. In particular, in [3] the Numerical Dispersion Mitigation network or NDM-net was suggested. The approach is essentially based on the necessity to solve numerous similar problems with different right-hand sides (different source positions). As a result, the training dataset can be constructed as an accurate enough solution for a small number of problems, and then the net is applied to fix the entire dataset. However, the generation of the training dataset assumes simulation of elastic wavefield using a fine-enough grid which is the most time and resource-consuming part of the method. Thus, it is worth minimizing the training dataset to improve the algorithm's performance. Recently, we suggested an approach to construct the training dataset preserving the particular value of the Hausdorff distance between the training dataset and the entire dataset [2]. This approach to dataset construction lets us reduce the number of the seismograms in the training dataset by a factor of three compared to equidistantly distributed sources. However, this approach still has a drawback. If the model has strong lateral inhomogeneities, such as dykes or salt intrusions, the average

distance between the seismograms may vary. Thus, the use of a low Hausdorff distance limit leads to an unreasonable dense set of sources involved in the training dataset in some areas. On the contrary, adjusting the limit to the worst case causes an underrepresentation of the data from relatively smooth parts of the model. To overcome this drawback, we suggest the adaptive training dataset construction, where the limiting distance between the training dataset and the entire dataset is adjusted to the model.

The remainder of the paper has the following structure. We describe the main concepts of seismic modeling and the NDM-net in Sect. 2. Different strategies for the training dataset construction are presented in Sect. 3. Numerical experiments illustrate the advantages of the suggested approach in Sect. 4.

2 Preliminaries

Seismic modeling aims to solve the elastic wave equation with multiple right-hand sides, providing the solution at the given surface (usually the free surface). The most commonly used approach to perform seismic modeling nowadays is the finite differences because they combine high computational efficiency with simplicity of implementation and complex models treatment [8,22,23]. The standard staggered grid schemes are commonly used to simulate wavefields in isotropic elastic media [7,21], which has the following representation in 2D:

$$\begin{gathered}
\hat{\rho}_{i+1/2,j} D_t[u_x]^{n+1/2}_{i+1/2,j} = D_x[\sigma_{xx}]^{n+1/2}_{i+1/2,j} + D_z[\sigma_{xz}]^{n+1/2}_{i+1/2,j}, \\
\hat{\rho}_{i,j+1/2} D_t[u_z]^{n+1/2}_{i,j+1/2} = D_x[\sigma_{xz}]^{n+1/2}_{i,j+1/2} + D_z[\sigma_{zz}]^{n+1/2}_{i,j+1/2}, \\
D_t[\sigma_{xx}]^{n}_{i,j} = (\lambda + 2\mu)_{i,j} D_x[u_x]^{n}_{i,j} + \lambda_{i,j} D_z[u_z]^{n}_{i,j} + (f_{xx})^{n}_{i,j}, \\
D_t[\sigma_{zz}]^{n}_{i,j} = \lambda_{i,j} D_x[u_x]^{n}_{i,j} + (\lambda + 2\mu)_{i,j} D_z[u_z]^{n}_{i,j} + (f_{zz})^{n}_{i,j}, \\
D_t[\sigma_{xz}]^{n}_{i+1/2,j+1/2} = \hat{\mu}_{i+1/2,j+1/2} \left(D_x[u_z]^{n}_{i+1/2,j+1/2} + D_z[u_x]^{n}_{i+1/2,j+1/2} \right) + \\
+ (f_{xz})^{n}_{i+1/2,j+1/2},
\end{gathered} \tag{1}$$

where $\boldsymbol{u} = (u_x, u_z)^T$ is the velocity vector, σ_{xx}, σ_{zz}, and σ_{xz} are the components of the stress tensor. The corresponding grid functions are defined at the staggered grid, so that $g^N_{I,J} = g(N\tau, Ih_x, Jh_z)$, where τ is the time step, h_x and h_z are the spatial steps, indices I, J, N can be either integer or half-integer and g is a smooth enough function. Functions f_{xx}, f_{zz}, and f_{xz} represent the right-hand side. Parameter ρ is the mass density, λ and μ are the Lame parameters. Typically all the model parameters are defined at the integer grid pints. In contrast, the arithmetic average for density and the harmonic average for μ are used to obtain them in the fractional points [14,23]. Operators D_t, D_x, and D_z are:

$$\begin{gathered}
D_t[g]^N_{I,J} = \frac{g^{N+1/2}_{I,J} - g^{N-1/2}_{I,J}}{\tau} = \frac{\partial g}{\partial t} + O(\tau^2), \\
D_x[g]^N_{I,J} = \frac{1}{h_x} \sum_{m=0}^{M} \left(g^N_{I+m+1/2,J} - g^N_{I-m-1/2,J} \right) = \frac{\partial g}{\partial x} + O(h_x^{2(m+1)}), \\
D_z[g]^N_{I,J} = \frac{1}{h_z} \sum_{m=0}^{M} \left(g^N_{I,J+m+1/2} - g^N_{I,J-m-1/2} \right) = \frac{\partial g}{\partial z} + O(h_z^{2(m+1)}).
\end{gathered} \tag{2}$$

Note that the scheme (1) approximates linear hyperbolic system, thus due to the Courant stability criterion $\tau = Ch$, where h can be considered as the $\min\{h_x, h_z\}$. Thus, we can consider the scheme depending only on parameter h.

In short notations, the finite-difference problem can be rewritten as:

$$R_h[\boldsymbol{v}_h] = \boldsymbol{\phi}_h(t)\delta(x - x_s^l)\delta(z - z_s^l),$$

where $\boldsymbol{\phi}(t)$ is the time impulse of the source, δ is the delta-function, (x_s^l, z_s^l) are the coordinates of the $l-$th source. Vector $\boldsymbol{v}_h$ is the vector of the solution combined with velocity vector components and the stress tensor components.

According to the theory of finite-difference schemes, if the scheme is stable and it approximates the original differential operator, then the numerical solution converges to the true solution, and the following estimation takes place:

$$\|\boldsymbol{v} - \boldsymbol{v}_h\| \leq Ch^r, \tag{3}$$

where the convergence rate r coincides with the order of approximation, which is 2 for the considered case. Constant C is independent of the grid step.

Consider now the scheme (1) but with two different grid steps $h_1 \leq h_2$. According to the estimation (3) one gets:

$$\|\boldsymbol{v} - \boldsymbol{v}_{h_1}\| \leq \|\boldsymbol{v} - \boldsymbol{v}_{h_2}\|.$$

However, using the smaller grid steps $h_1 \leq h_2$ leads to the problem size increase. The idea of the NDM-net is to construct a map:

$$\mathcal{M}[\boldsymbol{v}_{h_2}] = \tilde{\boldsymbol{v}}_{h_2},$$

so that

$$\|\tilde{\boldsymbol{v}}_{h_2} - \boldsymbol{v}_{h_1}\| \leq \varepsilon_{21} << Ch_2^r.$$

If the error ε_{12} is small one gets:

$$\|\tilde{\boldsymbol{v}}_{h_2} - \boldsymbol{v}\| \leq \|\tilde{\boldsymbol{v}}_{h_2} - \boldsymbol{v}_{h_1}\| + \|\boldsymbol{v}_{h_1} - \boldsymbol{v}\| \leq \varepsilon_{21} + Ch_1^r < Ch_2.$$

In other words, we suggest using NDM-net to map the data computed on a coarse mesh to the data computed using a fine enough grid.

In our research, we apply the Convolutional Neural Network (CNN), and in particular, a U-Net [3,16]. As it was mentioned above, the most time-consuming part of the NDM-net implementation is the generation of the training dataset, which is the simulation of the wavefield for a small number of sources using a fine enough grid. We suggest optimizing the choice of sources to minimize the training dataset and, thus, improve the NDM-net performance.

3 Training Dataset Construction Approaches

In this paper, we discuss three ways to construct training datasets. Two of them were presented in [3] and [2]; the third one is new and will be compared against the other two.

3.1 Equidistantly Distributed Seismograms

The first approach was suggested together with NDM-net in [3]. Introduce a seismogram corresponding to a fixed source number l as:

$$\boldsymbol{u}^l = \boldsymbol{u}(t, x, z_0, x_s^l, z_s^l),$$

where $\boldsymbol{u}$ is the velocity vector. We need to point out that it is convenient to introduce a change of variables $x_o = x - x_s^l$, variable x_o is called the offset, and it is fixed for all source positions. As a result, the seismic data can be viewed as a set of 2D functions of time and offset or a single 3D function of time, offset and source position. We prefer the first option, thus, the entire set of seismograms can be represented as:

$$U = \bigcup_{l=1,\dots,L_s} \boldsymbol{u}(x_s^l, x_o, t) = \bigcup_{l=1,\dots,L_s} \boldsymbol{u}(\boldsymbol{x}_s^l),$$

and our goal is to construct the subset

$$U^{tr} = \bigcup_{l \in M_t} \boldsymbol{u}(\boldsymbol{x}_s^l) \subseteq U,$$

where M_t is the set of indices of the seismograms from the subset; i.e., $M_t \subseteq \{1, ..., J_L\}$.

The first approach to construct the dataset U^{tr} was implemented to preserve the Housdorff distance between the training dataset and the entire dataset, where the distance is measured as the physical distance between the source positions. The Hausdorff distance between two sets D_1 and D_2 is defined as

$$\begin{aligned} H(D_1, D_2) &= \max\{\max_{i \in L_1} b(\boldsymbol{u}_i, D_2), \max_{j \in L_2} b(\boldsymbol{u}_j, D_1)\} = \\ &= \max\{\max_{i \in L_1} \min_{j \in L_2} d(\boldsymbol{u}_i, \boldsymbol{u}_j), \max_{j \in L_2} \min_{i \in L_1} d(\boldsymbol{u}_j, \boldsymbol{u}_i)\}. \end{aligned}$$

where

$$b(\boldsymbol{u}_i, D_2) = \min_{j \in L_2} d(\boldsymbol{u}_i, \boldsymbol{u}_j),$$

is the distance between an element $\boldsymbol{u}_i$ and the set D_2, and $d(\boldsymbol{u}_i, \boldsymbol{u}_j)$ is the distance between two elements (seismorgamms).

We are interested in the distance between the training dataset D_t and the entire dataset U with $D_t \subset U$. Thus,

$$H(D_t, U) = \max_{i \in [1,\dots,J_s]} b(\boldsymbol{u}_i, D_t) = \max_{i \in [1,\dots,J_s]} \min_{j \in J_t} d(\boldsymbol{u}_i, \boldsymbol{u}_j).$$

Let us consider the distance $d(\boldsymbol{u}_i, \boldsymbol{u}_j) = |x_s^i - x_s^j|$, and require the corresponding Hausdorff distance to be fixed at value $M \cdot ds$, where M is an integer number, and ds is the distance between two neighboring sources (typically fixed for a seismic acquisition system). We get the training datasets U_s^N.

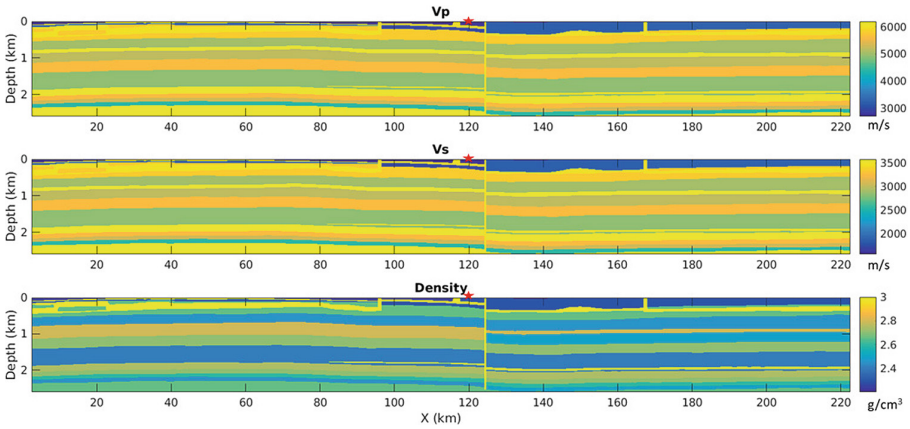

Fig. 1. Vanavar model

3.2 NRMS-Based Distance Between the Seismogramms

The second approach to construct the training dataset is based on preserving the Hausdorff distance but using the similarity measure between two seismograms instead of the indirect measure based on the distance between the sources. The similarity of the seismograms is often measured by the Normalized Root Mean Square of NRMS:

$$NRMS(a_t, b_t, t_0) = \frac{200 \times RMS(a_t - b_t)}{RMS(a_t) + RMS(b_t)},$$

where the RMS is defined as:

$$RMS(x_t) = \sqrt{\frac{\sum_{t_0-dt}^{t_0+dt} x_t^2}{N}},$$

and N is the number of samples in the interval $[t_0 - dt, t_0 + dt]$. We introduce the distance $d(\boldsymbol{u}^j, \boldsymbol{u}^k)$ as an average NRMS between $\boldsymbol{u}^j$ and $\boldsymbol{u}^k$ seismograms.

Having introduced this measure, one may define the Hausdorff distance and construct the training datasets to preserve this distance. We will denote such datasets U^Q_{NRMS}, where Q represents the particular value of NRMS in percentages.

To illustrate the construction of the dataset we consider a model presented in Fig. 1.

We simulated two sets of seismograms for this model, using grids with the step 2.5 m and 5 m. The entire datasets contain a 1901 seismogram with the sources placed 100 m apart from each other. After that, we constructed the training datasets and then computed the NRMS-based distances $b(\boldsymbol{u}_i, D_t)$ between each seismogram and the training datasets as a function of the source position. Figure 2 represents the distances to datasets U_s, and Fig. 3 illustrates the

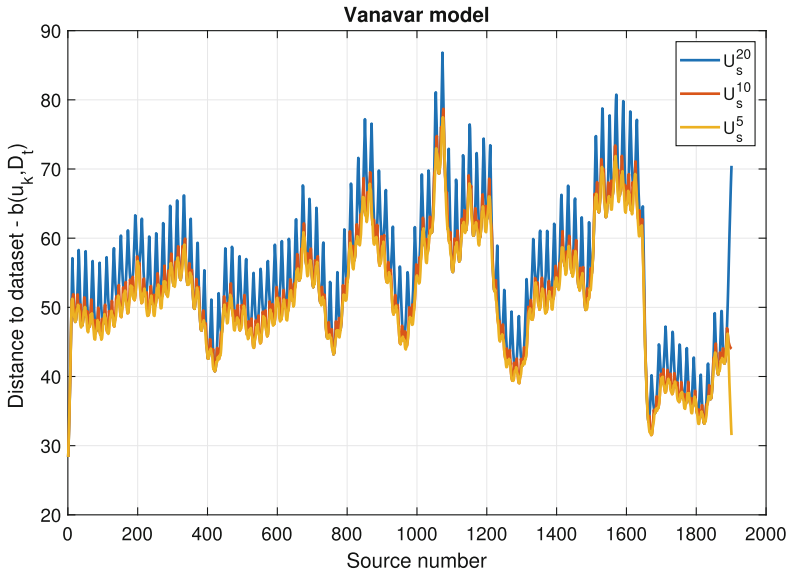

Fig. 2. Distances from the seismograms and the training datasets $b(\boldsymbol{u}^k, U_s^N)$ for different dataset of equidistantly distributed source U_s^5, U_s^{10}, and U_s^{20}.

distances to the dataset U_{NRMS}^{70}. Note that in the second case, we manage to preserve the maximal distance to the training dataset. However, there are domains where almost all seismograms were used, which strongly affects the algorithm's performance.

3.3 Adaptive Dataset Construction

As it follows from Fig. 2, NRMS between the seismograms corresponding to the neighboring sources may vary depending on the source position, and just a formal dissimilarity of the seismograms may not be the reliable criterion for dataset construction. In this paper, we suggest combining the two approaches so that we will choose the limiting NRMS distance to the training dataset, depending on the physical position of the sources. We introduced several levels of the Hausdorff distance limits in the NRMS metric. To do so, we considered the mean NRMS between the seismograms and its standard deviation as the function of the distance between the sources, as presented in Fig. 4. We constructed the limits recurrently as follows:

- $L_1 =< NRMS(1) > +\alpha\sigma(1)$, where $< NRMS(1) >$ is the mean NRMS at a distance $1 \cdot ds$, and $\sigma(1)$ is the standard deviation of the NRMS for the sources at a distance $1 \cdot ds$, and α is a parameter to be changed.
- Start the recursion:

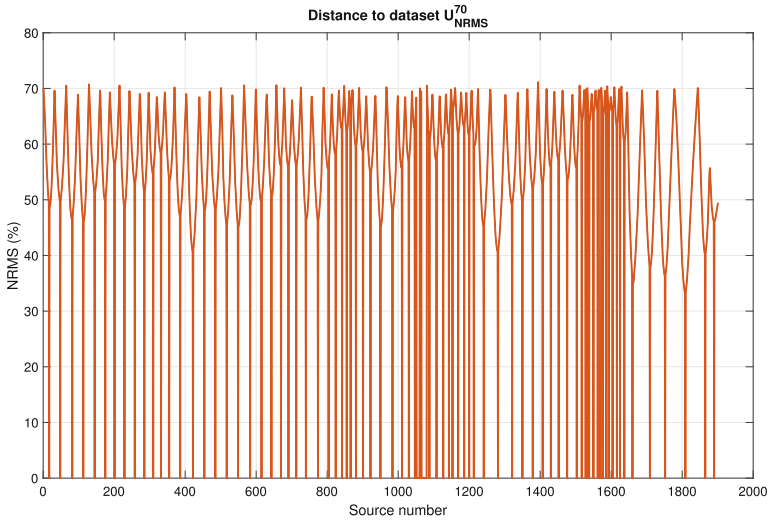

Fig. 3. Distance from the seismograms and the training dataset $b(\boldsymbol{u}^k, D^{70}_{NRMS})$.

- Solve the problem $\Delta_j = argmin|L_{j-1} - < NRMS(\Delta) > |$, where Δ_j is the physical distance between the sources.
- $L_j =< NRMS(\Delta_j) > +\alpha\sigma(\Delta_j)$

The algorithm stops if the solution of the *argmin* problem is the maximum of Δ. There is a parameter in this algorithm that is subject to change.

Constructing the set of limiting NRMS values, we may apply the procedure of the dataset generation according to the rule:

- start from the seismogram number 1, subset 1;
- accumulate the seismograms (in ascending order) to the current cluster while

$$\min_{i \in C_k} \max_{j \neq i} d(\boldsymbol{u}_i, \boldsymbol{u}_j) \leq L_m$$

  where i and j are indices of the seismograms from the current cluster C_k, and m is a current NRMS limit (which starts from one for a new cluster).
- if the set contains enough seismograms, which is

$$\min_{i \in U_k} \max_{j \neq i} |x^i_s - x^j_s| \geq R,$$

  we state that the cluster is complete, and the new element of the training dataset is the solution to the problem:

$$I_k = argmin_{i \in C_k} \max_{j \neq i} d(\boldsymbol{u}_i, \boldsymbol{u}_j).$$

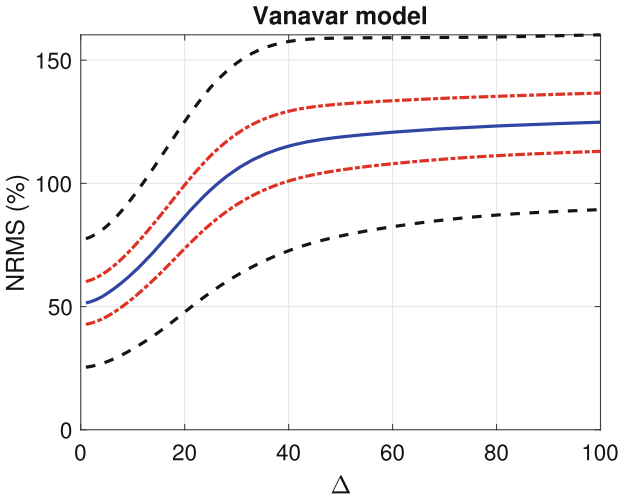

Fig. 4. Mean (solid line), STD (dash-dotted), and 3 STD (dashed) of NRMS-distance as a function of the distance between the sources.

– if the current set contains a small number of seismograms which is

$$\min_{i \in U_k} \max_{j \neq i} |x_s^i - x_s^j| < R,$$

then we update NRMS limit to L_{m+1} and continue collecting seismogramms to the cluster.

This algorithm allows for overcoming the situation where the seismograms in the training dataset correspond to unreasonably close sources.

4 Numerical Experiments

4.1 Effect of the Parameters

First, we studied the effect of the parameters used in the algorithm on the number of seismograms in the training dataset. There are two empirically adjusted parameters: α, the coefficient defining the increase in the limiting NRMS level, and R, which governs the minimal number of seismograms in a cluster. Change in the minimal distance between the sources R would directly affect the number of seismograms in the training dataset. In particular, the higher R is, the fewer seismograms will be used. Moreover, the following estimate takes place $N_{cl} \leq N_{sg} \cdot ds/R$, where N_{cl} is the number of clusters or the number of seismograms in the training dataset, N_{sg} the total number of seismograms. The effect of α is less evident because α directly affects the segmentation of the limiting NRMS level, not the number of seismograms. However, the use of too small α would lead to the very fine discretization of the limiting NRMS. Thus, only the

physical proximity of the sources will govern the training dataset construction. We consider these two parameters varied as follows $R \in \{2, 5, 10, 20, 50\}$, and $\alpha \in \{0.2, 0.5, 0.7, 0.9, 1, 1.2, 1.5, 2, 3\}$. Table 1 presents the relation between the parameter α and the number of the segmentation levels of the limiting NRMS. As expected, the higher α, the smaller the number of segmentation levels. Similarly, when α increases, the number of clusters gets smaller (Table 2). It is due to the rapid increase of the limiting NRMS level that wider clusters of seismograms are allowed to form. The number of clusters increases with the decrease of the minimal distance between the sources, as expected. In general, the number of clusters varies slightly with the change of limiting distance (at least for intermediate values of α). However, for $R = 50 \cdot ds$, the number of clusters decreased significantly, making the training dataset underrepresentative.

Table 1. Number of segmentation levels for different α.

α	0.2	0.5	0.7	0.9	1	1.2	1.5	2	3
N_L	30	12	9	7	6	5	5	4	3

Table 2. Number of seismograms in the training dataset for different α and R.

$R \setminus \alpha$	0.2	0.5	0.7	0.9	1	1.2	1.5	2	3
2	197	135	117	110	104	96	84	75	58
5	165	129	111	108	101	94	83	74	58
10	131	110	100	92	92	88	80	71	56
20	85	78	75	73	73	70	66	62	52
50	37	35	34	32	32	32	17	10	8

4.2 Implementation of the NDM-Net

In our further study, we focused on two scenarios with $R = 10 \cdot ds$ in both cases and $\alpha = 0.9$ and $\alpha = 1.2$. We trained the NDM-net using two adaptive datasets and compared the results against our previous results, obtained with the training datasets with equidistantly distributed sources and with the NRMS-preserving technique. The NDM-net setup was the same for all numerical experiments as described in [3]. Having trained the NDM-net, we applied it to the entire dataset and compared the results with the accurate solution computed on the fine mesh. Figures 5 and 6 provide the seismogramm-by-seismogramm NRMS distances between the accurate and predicted solutions for the datasets constructed preserving NRMS and using the adaptive technique, respectively. Both approaches illustrate similar accuracy of the seismogram prediction. To make a qualitative comparison, it is worth computing an average NRMS over all seismograms and considering the number of seismograms in the training dataset.

In addition, we add the data corresponding to equidistantly distributed sources to complete the comparison. All data is provided in Table 3 and Fig. 7. Note that the proposed adaptive dataset construction illustrates both superiority in accuracy and the number of seismograms used in the training dataset.

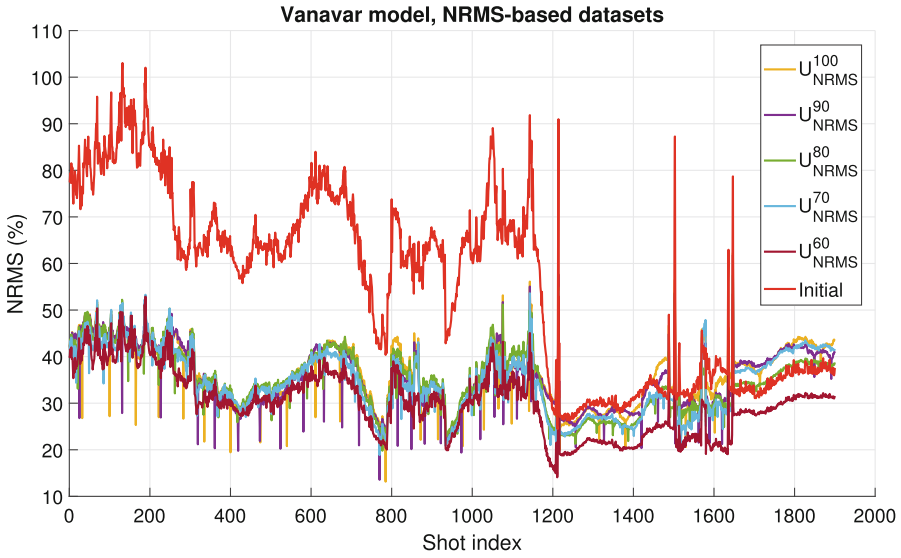

Fig. 5. seismogramm-by-seismogramm NRMS distances between the fine-grid solution and NDM-net corrected solutions for different training datasets based on the NRMS preserving.

5 Conclusions

This study presented a new strategy to construct the training dataset for the numerical dispersion mitigation network or NDM-net. In opposite to the two previous approaches, where the Hausdorff distance from the training dataset to the entire dataset was preserved globally, the new approach is adaptive which allows avoiding the use of unreasonably dense training datasets. In particular, in the previous works, the datasets were constructed to preserve the Hausdorff distance based on the Euclidean distance between the source positions. The resulting datasets consisted of the seismograms corresponding to the equidistantly distributed sources, with no information about the data proximity or dissimilarity accounted for. The other approach was based on the preservation of the distance measured in the data space. In particular, the NRMS measure of seismogram similarity was used. This method reduced the number of seismograms in the training dataset by a factor of three compared with equidistantly distributed sources. However, this approach may lead to the unreasonably dense spatial distribution of the sources corresponding to the seismograms from the

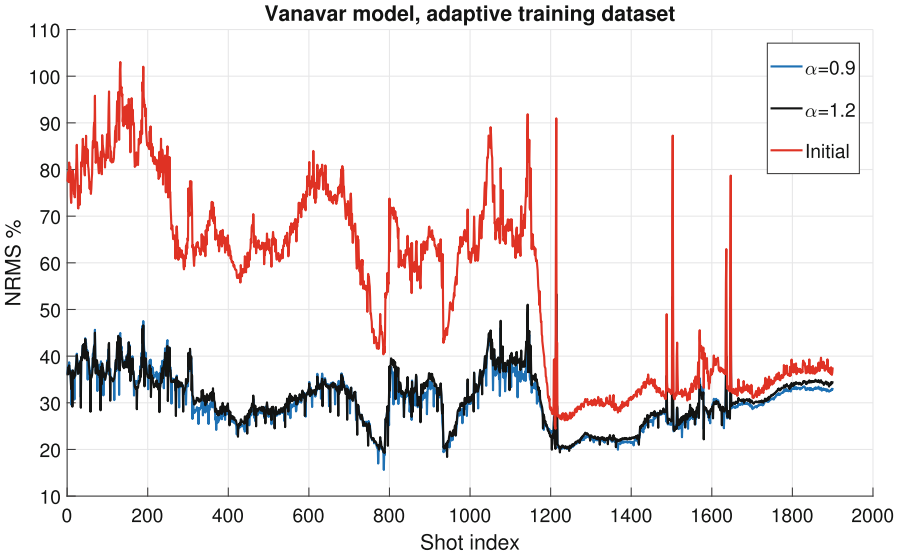

Fig. 6. seismogramm-by-seismogramm NRMS distances between the fine-grid solution and NDM-net corrected solutions for different training datasets constructed using the adaptive technique.

Table 3. Number of seismograms and resulting NRMS for different strategies of training datasets constructions

NRMS-preserving datasets		
Dataset	Number of sources	average NRMS
U^{60}_{NRMS}	414	28.16%
U^{70}_{NRMS}	109	30.28%
U^{80}_{NRMS}	56	34.69%
U^{90}_{NRMS}	43	35.11%
U^{100}_{NRMS}	34	35.68%
equidistantly distributed sources		
Dataset	Number of sources	average NRMS
U^{5}_{s}	86	44.28%
U^{10}_{s}	191	31.91%
D^{20}_{s}	283	29.41%
adaptive datasets		
Dataset	Number of sources	average NRMS
$U^{\alpha=0.9}$	92	30.32%
$U^{\alpha=1.9}$	88	30.83%

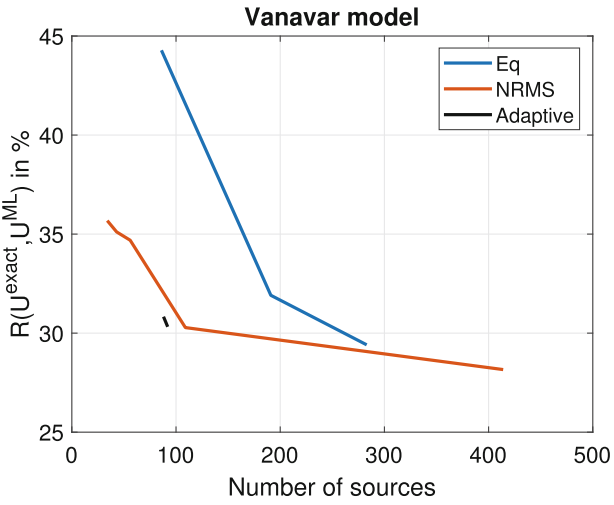

Fig. 7. The error depending on the number of seismograms used in the training dataset for different strategies of training dataset construction.

training dataset because of the local complexities of the model. Moreover, the two presented approaches require empirically chosen input parameters (the limiting Hausdorff distance) which strongly affect the result.

To overcome the drawbacks of the two approaches, we suggested a new strategy that adjusts the distance to the training dataset according to the current data. In particular, we introduce the segmented levels of limiting NRMS based on the mean of NRMS for different distances between the sources over the entire dataset. After that, we applied the procedure of constructing the training dataset with preserved NRMS. If the sources corresponding to the training dataset appears to be close to each other, we locally increase to limiting NRMS level, according to the segmented levels. We illustrated that this approach provides the tiniest training datasets among the three considered methods. Moreover, using the adaptive training dataset produces the lowest error of the NDM-net implementation. Additionally, the adaptive approach does not require input parameters calibration because it produces stable results for the appropriate set of parameters.

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Numerical Evaluating the Permeability of Rocks Based on Correlation Dependence on Geometry

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Abstract. We present a resource-saving algorithm for numerical evaluation of the absolute permeability of a rock from the sample's CT-images of huge size, which makes it possible to perform such an assessment using limited computing resources, in particular, personal computers. It is based on a decomposition of the 3D sample image into small representative sub-samples, for which the absolute permeability is estimated based on the numerical solution of the Stokes equation in a static formulation, followed by a creation of the functional dependencies between the permeability and open porosity. After that these dependencies can be extended to the entire original sample or to the full-sized core sample.

Keywords: Permeability · numerical estimation · porosity · correlation dependence · scaling · digital rock physics · CT-images

1 Introduction

Digital rock physics is a modern field of computational physics used to simulate various processes at the scale of rocks pores. The models of rock including the pore space and the rock skeleton are built from 3D CT-images with using different image segmentation methods [1]. The result is a three-dimensional grid model with a finite (small) number of different components representing different fluids in the pore space or minerals in the skeleton. After that, for each voxel the appropriate physical properties are assigned and the required physical field is calculated.

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One of the main areas of digital rock physics is the upscaling properties of rocks for their further using in macroscale models. In particular, numerical upscaling is widely used to estimate the absolute and relative permeability [2,6,7,14,17], elastic parameters [9,10,19], electrical resistivity [2,13,16] and many other parameters. At the same time, the size and resolution of tomographic images are determined by the apparatus [15], in particular, modern microtomographs make it possible to obtain an image with a resolution up to 0.5 micron per voxel and a size up to 4000 voxels in each direction. So the working image size without edge effects is about 2000 voxels. As a result, the computational grid for problems is about $10^9 - 10^{10}$ points. At the same time, the physical sizes of the computational domain are the first millimeters, which, of course, raises the question of representativeness of the considered volume [4]. In this work it is shown that the geometric characteristics of the pore space are determined quite stably on the indicated dimensions, however, these dimensions are often insufficient for evaluation of the physical properties of the samples. Therefore, at present, the methods of computational rocks physics are applied to solve the set of problems for different sample sizes and to accumulate statistical data [11]. An alternative direction is geostatistical modeling of rock samples using multi-point statistics, or machine learning methods [12]. The first approach is more common, which is mainly related to the computational aspects of the tasks being decided. Solving a series of independent problems with the accumulation of statistics is an example of parallelization by tasks, where the scalability of the algorithm is 100%, i.e. there is no loss on overhead transactions and data exchange. At the same time, the size of each task allows you to perform simulation using a small number of graphics co-processors (GPUs), opening up the possibility of modeling at workstations, which is relevant for geophysical laboratories with limited access to computing resources [8]. This paper develops the approach proposed in [11], which proposes to accumulate statistics on a large set of subsamples with subsequent construction of functional dependencies between the estimated parameters and sample porosity.

2 Evaluating the Absolute Permeability of Rock

2.1 Mathematical Statement of the Problem

To evaluate the absolute permeability of rock it is necessary to calculate the steady-state flow of a viscous incompressible fluid in a pore space. We've got the model of the rock sample obtained by binary segmentation of CT-images. Formally, the mathematical statement of the problem is as follows. The stationary Stokes equation is considered:

$$\begin{aligned} \mu \Delta \vec{u} - \nabla p = 0, \\ \nabla \cdot \vec{u} = 0, \end{aligned} \tag{1}$$

defined in the pore space

$$\Omega_p \subseteq \Omega = [0, X_1] \times [0, X_2] \times [0, X_3],$$

where $\vec{u} = \vec{u}(\vec{x})$ is the velocity vector of fluid flow, $p = p(\vec{x})$ is the pressure, μ is the fluid viscosity. On two opposite sides of the computational domain, the pressure values are assumed to be defined, and the tangential velocity components are equal to zero:

$$\begin{aligned} p(\vec{x})\big|_{x_1=0} &= p_0, \qquad & p(\vec{x})|_{x_1=X_1} &= p_1, \\ \vec{u} \times \vec{n}\big|_{x_1=0} &= 0, \qquad & \vec{u} \times \vec{n}\big|_{x_1=X_1} &= 0, \end{aligned}$$

where x_1 is the spatial coordinate in the direction of pressure changing. The adhesion conditions are defined at the outer boundaries and at the boundary between the pore space and rock matrix:

$$\vec{u}\big|_B = 0.$$

The solution of Stokes Eq. (1) determines the fluid velocity field and the pressure distribution. So the fluid flow through the sample can then be calculated as:

$$Q_x = \int_0^{X_2} \int_0^{X_3} u_1 dx_2 dx_3,$$

where Q_x is the fluid flow, u_1 is the flow velocity in the direction of pressure changing.

On the other hand, the fluid flow in a porous medium satisfies the Darcy equation:

$$Q_x = -\frac{S\kappa}{\mu} \frac{(p_1 - p_0)}{X_1},$$

where $S = X_2 X_3$ is the cross-sectional area of the sample, κ is the absolute permeability. As a result, knowing the fluid flow through the sample at a given pressure drop, the permeability can be estimated as

$$\kappa = -\frac{\mu X_1}{(p_1 - p_0)S} Q_x,$$

The solution of the Stokes equation is the main part of the absolute permeability estimation algorithm. To construct a stationary solution, the method of establishment is used, namely, the solution of the Stokes equation is constructed as an asymptotic steady-state solution of the non-stationary Navier-Stokes equation, in which the influence of convective terms is neglected due to the low flow velocity:

$$\begin{gathered} \frac{\partial \vec{u}}{\partial t} = -\nabla p + \mu \Delta \vec{u}, \\ \nabla \cdot \vec{u} = 0, \end{gathered}$$

Here it is necessary to supplement the problem with initial conditions, which are assumed to be zero.

2.2 Numerical Solution of the Navier-Stokes Equation

For the numerical solution of the Navier-Stokes equation, the projection method is used, the essence of which is a two-stage calculation of the solution. Let the solution at the time layer $t^n = n\tau$ is defined, and it is necessary to calculate the solution at the layer t^{n+1}. At the first step of the algorithm, a preliminary calculation of the speed is carried out, which may not satisfy the continuity equation. In the second step, the pressure is calculated to provide the necessary velocity correction to satisfy the continuity equation, after which the velocity is corrected.

$$\begin{gathered}\frac{\vec{u}^*-\vec{u}^n}{dt} = \mu\Delta\vec{u}^n,\\ \frac{\vec{u}^{n+1}-\vec{u}^*}{dt} = -\nabla p^{n+1},\\ \nabla\cdot\vec{u}^{n+1} = 0,\end{gathered}$$

where $\vec{u}^n$, $\vec{u}^{n+1}$ are the velocities at the time layers t^n and t^{n+1} accordingly, $\vec{u}^*$ - auxiliary velocity vector, p^{n+1} is the pressure in the fluid at the time layer t^{n+1}.

From the last two equations, one can get:

$$\begin{gathered}\frac{\vec{u}^*-\vec{u}^n}{dt} = \mu\Delta\vec{u}^n,\\ \Delta p^{n+1} = \frac{\nabla\cdot\vec{u}^*}{dt},\\ \frac{\vec{u}^{n+1}-\vec{u}^*}{dt} = -\nabla p^{n+1}.\end{gathered}$$

This equations system determines the projection method for solving the Navier-Stokes equation. It can be seen that the prediction and correction of the velocity is carried out by a method, which is explicit in time, while the correction of pressure requires the solution of the Poisson equation in the pore space.

Spatial discretization is based on the finite difference method using a staggered grid scheme. Grid functions are defined as

$$\begin{gathered}p_{i,j,k} = p(ih_1, jh_2, kh_3), \qquad (u_1)_{i+1/2,j,k} = u_1((i+1/2)h_1, jh_2, kh_3),\\ (u_2)_{i,j+1/2,k} = u_2(ih_1, (j+1/2)h_2, kh_3),\ (u_3)_{i,j,k+1/2} = u_3(ih_1, jh_2, (k+1/2)h_3),\end{gathered}$$

where h_1, h_2, h_3 are the spatial grid steps, i, j, k are the ordinal numbers of the grid cell. Further, it can be used the operators that approximate second-order differential operators:

$$\begin{gathered}L[f]_{I,J,K} = D_1^2[f]_{I,J,K} + D_2^2[f]_{I,J,K} + D_3^2[f]_{I,J,K} = \Delta f + O(h^2),\\ D_1^2[f]_{I,J,K} = \frac{f_{I+1,J,K}-2f_{I,J,K}+f_{I-1,J,K}}{h_1^2} = \left.\frac{\partial^2 f}{\partial x_1^2}\right|_{I,J,K} + O(h_1^2),\\ D_1^c[f]_{I,J,K} = \frac{f_{I+1/2,J,K}-f_{I-1/2,J,K}}{h_1} = \left.\frac{\partial f}{\partial x_1}\right|_{I,J,K} + O(h_1^2),\end{gathered}$$

where L is a finite-difference operator approximating the Laplace operator, f is a sufficiently smooth function, D_1^c, D_2^c, D_3^c are finite-difference operators approximating the first spatial derivatives, D_1^2, D_2^2, D_3^2 are finite-difference operators approximating the second spatial derivatives. Here indices written in capital letters can take both integer and half-integer values. By appropriately substituting

indices, one can obtain operators that approximate derivatives in other spatial directions.

Using the introduced notation, the approximation of the Navier-Stokes equations (projection method) can be written as:

$$\begin{gathered}
\frac{(u_1^*)_{i+1/2,j,k}-(u_1^n)_{i+1/2,j,k}}{\tau}+\mu L[u_1^n]_{i+1/2,j,k}=0,\\
\frac{(u_2^*)_{i,j+1/2,k}-(u_2^n)_{i,j+1/2,k}}{\tau}+\mu L[u_2^n]_{i,j+1/2,k}=0,\\
\frac{(u_3^*)_{i,j,k+1/2}-(u_3^n)_{i,j,k+1/2}}{\tau}+\mu L[u_3^n]_{i,j,k+1/2}=0,\\
L[p^{n+1}]_{i,j,k}=\frac{D_1^c[u_1^*]_{i,j,k}+D_2^c[u_2^*]_{i,j,k}+D_3^c[u_3^*]_{i,j,k}}{\tau},
\end{gathered}$$

$$\frac{(u_1^{n+1})_{i+1/2,j,k}-(u_1^*)_{i+1/2,j,k}}{\tau}-D_1^c[p^{n+1}]_{i+1/2,j,k}=0,$$

$$\begin{gathered}
\frac{(u_2^{n+1})_{i,j+1/2,k}-(u_2^*)_{i,j+1/2,k}}{\tau}-D_2^c[p^{n+1}]_{i,j+1/2,k}=0,\\
\frac{(u_3^{n+1})_{i,j,k+1/2}-(u_3^*)_{i,j,k+1/2}}{\tau}-D_3^c[p^{n+1}]_{i,j,k+1/2}=0.
\end{gathered}$$

2.3 Algorithm Verification

To verify the algorithm, we considered a model for which an analytical solution is known. We considered impermeable samples with a cylindrical channel of circular cross section connecting opposite faces of the sample. In this case, there is an analytical solution of the Stokes equation, which makes it possible to construct the flow and estimate the absolute permeability

$$k=\frac{\pi R^4}{8S},$$

where k is the absolute permeability, R is the radius of the cylindrical channel and S is cross-sectional area of the sample.

The experiments were carried out for a fixed sample size equal to 80^3 voxels. The grid step was chosen equal to 1 m, the hole radius varied from 5 to 40 points (the limiting case implied impermeable side boundaries, where the channel touched the model boundaries). The simulation results are shown in Table 1.

Table 1. Verification of the permeability estimation algorithm. Results for a model with a cylindrical channel.

Hole radius	Theoretical evaluation	Simulation result	Relative error
5	0.038348	0.039277	2.4234%
10	0.613574	0.620464	1.123%
20	9.817187	9.870730	0.5454%
40	157.075	157.4713	0.2523%

3 Evaluation by Trend Using the Correlation Dependence on Geometry

In this study, we are based on the research performed by [11], which states that it is important not just to obtain fixed values of permeability or other parameters for a particular sample, but to reconstruct the statistical trends between geometry parameter (for example, porosity) and evaluated parameter, which is the absolute permeability in our case. In our research, we use the assumption that the total sample is large enough to be divided into representative sub-samples, at least, for the pore space geometry. As a result, we can evaluate the absolute permeability independently for each sub-sample and then construct correlation dependence between the permeability and porosity. So the estimated permeability can then be expanded to the total sample, full-sized core sample and so on.

3.1 Limestone Images Description

We consider four samples of limestone of the Medium Carboniferous system. They were originally cylindrical, with a length of 4 cm and a diameter of 3 cm. These samples were tested for porosity (through the fluid saturation method) and absolute permeability. Following that, the cubical sub-samples of 2 cm in size were taken out and specified measurements were performed. Later, the tiniest cubical sub-samples of 0.4 cm in size were extracted and scanned. It should be noted that the porosity of the smallest samples was also tested, but the permeability was not measured for them. As for the measurement error, when assessing porosity, it was 0.008–0.022% for cylindrical samples, 0.034–0.115% for medium samples and 4.567–11.27% for smallest samples. Table 2 shows the results of the laboratory measurements.

Table 2. The results of the laboratory measurements for the samples of various sizes.

Sample size	Sample No.	Porosity	Permeability (mD)		
			X	Y	Z
Large cylindrical	s07	0.156	26.3		
	s25	0.159	16.99		
	s31	0.191	40.93		
	s78	0.232	1684.10		
Medium cubical	s07	0.152	8.27	6.67	1.39
	s25	0.161	24.92	24.61	15.53
	s31	0.185	20.66	19.71	18.78
	s78	0.255	2527.7	2425.5	2243.9
Small cubical	s07	0.201	–		
	s25	0.128	–		
	s31	0.180	–		
	s78	0.288	–		

As we mentioned, the smallest samples were scanned, the resolution of CT-tomography was 3 μm per voxel and the sizes of obtained images were 1600–1800 voxels in each direction. After image pre-processing, including cropping to a region that lies completely within the target, non-correlated noise suppression based on the non-local mean Gauss filter method [5], and image segmentation by Otsu method [18] to separate the pore space and rock matrix without taking into account its mineral composition, we've obtained images of 1200^3 voxels, the cross-sections of which are shown in Fig. 1.

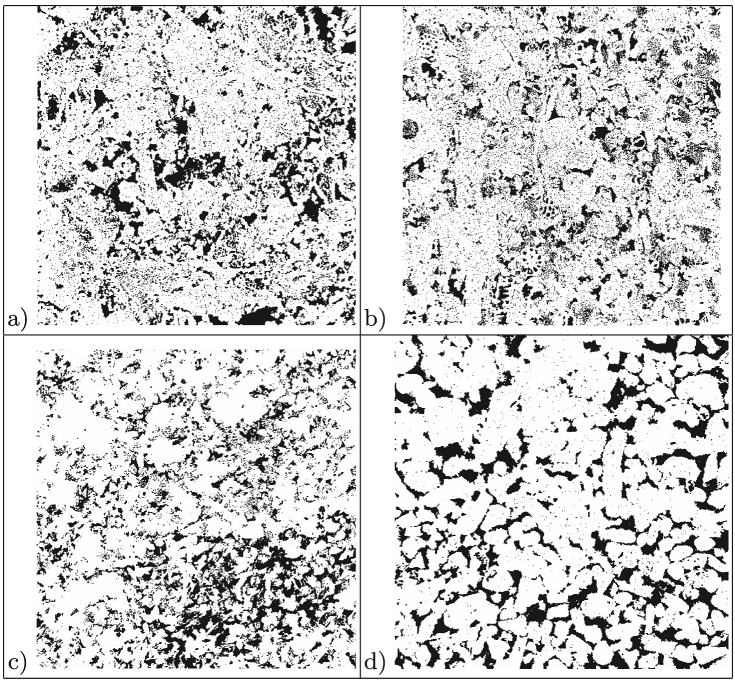

Fig. 1. 2D sections of the segmented images for the samples: a) no. 7; b) no. 25; c) no. 31; d) no. 78.

3.2 Methodology of Estimation

For numerical simulations, each sample was divided into 216 non-overlapping cubic sub-samples of 200^3 voxels, that is, the division occurred into 6 parts in each direction. This size of sub-sample was chosen taking into account the memory limitations of the GPU (nVidia GeForce 2090Ti with 12 GB of RAM). Then for each sub-sample, we calculated the total and open porosity, as well as the mean and standard deviation for these parameters over an ensemble of sub-samples. Note that the total porosity of the sample is defined as the ratio of the number of voxels corresponding to the pore space to the total number of voxels. Connected porosity includes only pores that form through channels connecting

opposite faces of the sample. That is, those pores that provide percolation of the sample. Moreover, the open porosity was calculated for each direction. The results of calculation are shown in Table 3. Here ϕ, ϕ_o are the porosity and open porosity respectively, $<>$ is the mean value and σ is the standard deviation.

Table 3. Mean values and standard deviations of porosity and open porosity in the X, Y, Z directions for the samples of limestone of Medium Carboniferous system.

Sample	$<\phi>$	$\sigma(\phi)$	$<\phi_o>_X$	$\sigma(\phi_o)_X$	$<\phi_o>_Y$	$\sigma(\phi_o)_Y$	$<\phi_o>_Z$	$\sigma(\phi_o)_Z$
no. 7	0.1473	0.0037	0.1259	0.005	0.1269	0.0051	0.1259	0.0037
no. 25	0.1223	0.0016	0.0938	0.0023	0.0936	0.0025	0.0938	0.0029
no. 31	0.1535	0.0042	0.1388	0.0047	0.1391	0.0051	0.1392	0.0048
no. 78	0.2112	0.0032	0.205	0.0035	0.2055	0.0034	0.2052	0.0032

It is worth noting that the open porosity is practically independent of spatial direction for all samples. Furthermore, the standard deviation for the porosity estimations is less than 5%, confirming the assumption about the statistical representativity of the investigated sub-samples. Based on the obtained values of porosity and open porosity, a linear regression can be constructed:

$$\phi_o = b_1\phi + b_0,$$

where b_0 and b_1 are the scalar coefficients. Figures 2 shows such linear regressions, while their formulas obtained for each considered models are given in Table 4.

Table 4. Linear regression relating open and total porosity of sub-samples.

Sample	Open porosity X	Open porosity Y	Open porosity Z
no. 7	$1.1163\phi - 0.0386$	$1.0954\phi - 0.0345$	$1.0987\phi - 0.0345$
no. 25	$0.9834\phi - 0.0265$	$0.9824\phi - 0.0265$	$0.9825\phi - 0.0264$
no. 31	$1.0769\phi - 0.0265$	$1.0752\phi - 0.026$	$1.0721\phi - 0.0254$
no. 78	$1.0222\phi - 0.0108$	$1.0151\phi - 0.0089$	$1.0146\phi - 0.0091$

Then we numerically simulate the fluid flow through the pores for each sub-sample, calculate the absolute permeability in all spatial directions as described in the previous section and construct the following dependence of this parameter on open porosity in logarithmic scale:

$$ln(\kappa) = b_0 ln(\phi_o) + b_1,$$

where κ is the absolute permeability, b_0 and b_1 are some constants. It is clear that we can write down a slightly different functional relationship between permeability and open porosity [3,11]:

$$\kappa = e^{b_1}\phi_o^{b_0} = c\phi_o^{b_0},$$

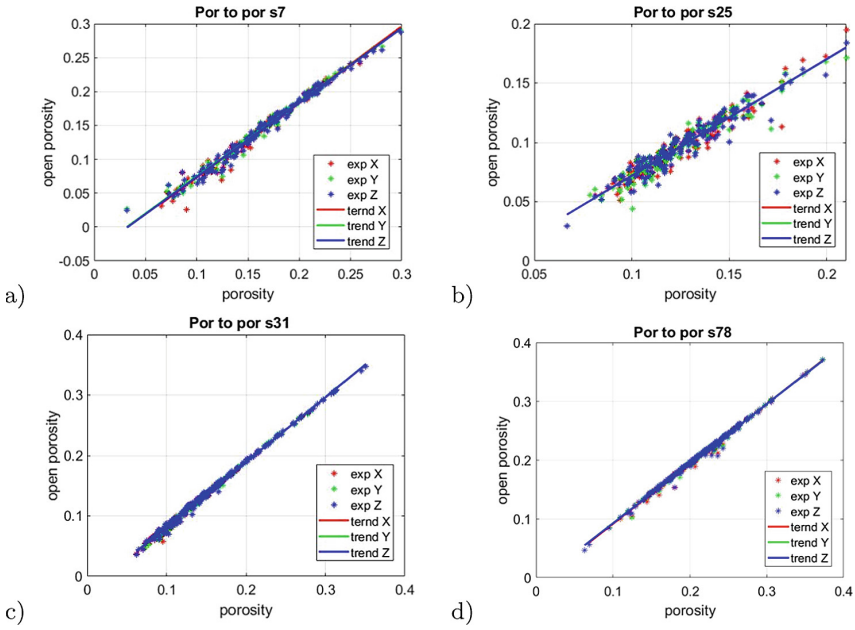

Fig. 2. Dependence of open porosity on total porosity and linear trends for the samples: a) no. 7; b) no. 25; c) no. 31; d) no. 78.

where b_0, b_1 and c are some constants. Illustrations of these dependencies are shown in the Figs. 3, 4, 5 and 6. The functional relationship between the porosity and absolute permeability for each spatial direction as well as the estimated values of the permeability for the total limestone samples are provided in Table 5. It can be seen that for all samples, the trends in different directions are very close to each other, which indicates that the samples are close to isotropic.

Table 5. Functional relationship between the open porosity and absolute permeability and the estimated values of the permeability (mD) for the total limestone samples.

Sample	Permeability X	κ_x	Permeability Y	κ_y	Permeability Z	κ_z
no. 7	$79.28\phi_o^{3.24}$	95.2	$52.58\phi_o^{3.14}$	80.3	$45.92\phi_o^{3.08}$	76.3
no. 25	$21.28\phi_o^{2.95}$	19.9	$25.41\phi_o^{3.05}$	18.4	$4.51\phi_o^{2.40}$	15.3
no. 31	$182.64\phi_o^{3.71}$	119.8	$205.23\phi_o^{4.02}$	73.5	$248.69\phi_o^{3.90}$	114.0
no. 78	$204.33\phi_o^{3.08}$	1554	$298.97\phi_o^{3.27}$	1685	$315.06\phi_o^{3.28}$	1744

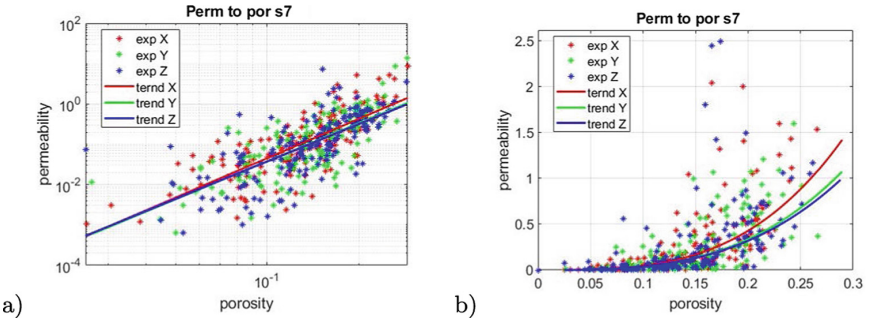

Fig. 3. Dependence of absolute permeability on porosity and trends for the sample no. 7: a) logarithmic scale; b) linear scale.

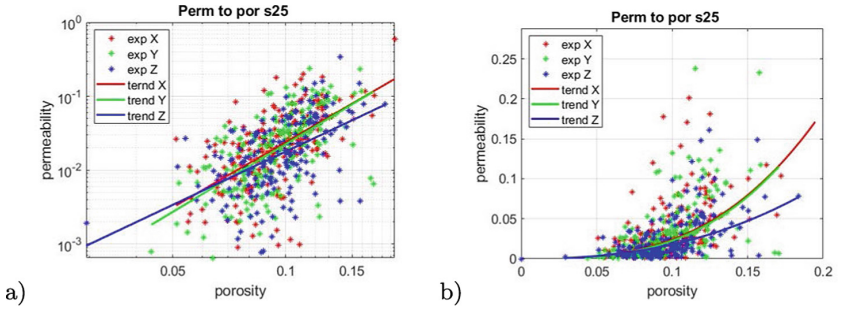

Fig. 4. Dependence of absolute permeability on porosity and trends for the sample no. 25: a) logarithmic scale; b) linear scale.

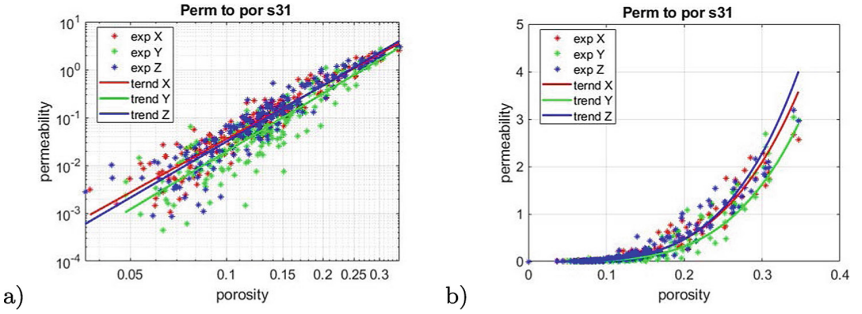

Fig. 5. Dependence of absolute permeability on porosity and trends for the sample no. 31: a) logarithmic scale; b) linear scale.

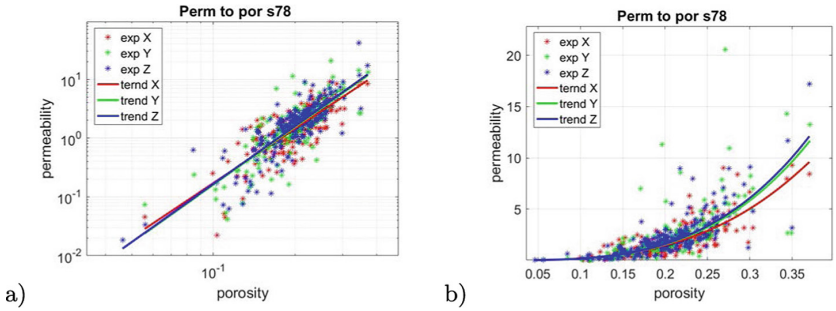

Fig. 6. Dependence of absolute permeability on porosity and trends for the sample no. 78: a) logarithmic scale; b) linear scale.

The comparison of numerical estimates with the results of laboratory experiments shows their similarity, which confirms the applicability of the proposed approach to the assessment of absolute permeability using the correlation dependence on geometry.

4 Conclusions

In this study, we presented the methodology for evaluating some basic parameters of rocks based on correlation dependence on geometry. The main idea of methodology is not to simulate fluid flows or other physical fields for the entire sample of huge size and calculate a single parameter value using supercomputers, but to use sub-samples of small but representative size for building a trend, i.e. a relation between the parameters under consideration, thus getting the ability to interpolate the simulation results to the required scale. Simulation of physical fields for small sub-images is possible using the personal computers, in our case a single desktop and nVidia GeForce 2090Ti with 12 GB of RAM was used, and it took only 10 h to calculate the permeability for 216 sub-samples. Thus, this approach can be easily used in any computational physics laboratory.

We have shown the applicability of the technique for evaluating the absolute permeability, but we assume that it can also be used when estimating other basic rock parameters: relative permeability, elastic moduli, formation factor, capillary pressure, etc. This thesis needs to be confirmed in the future.

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Computational Modeling of Temperature-Dependent Wavefields in Fluid-Saturated Porous Media

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Abstract. A computational model is presented for simulations small amplitude wavefields in a deformable porous medium saturated with a compressible fluid under temperature variations. The model is based on the governing equations derived with the use of the theory of Symmetric Hyperbolic Thermodynamically Compatible (SHTC) systems in conjunction with the efficient staggered grid finite difference numerical method. It is numerically shown that the characteristics of wavefields in a saturated porous medium strongly depend on the porosity, which varies with temperature.

Keywords: Wavefield simulation · Fluid saturated porous medium · Staggered Grid Finite Difference Scheme

1 Introduction

Modeling of wave processes in porous media is of interest for many practical problems of applied geophysics. This area of research is becoming especially relevant in connection with the development of digital technologies for twins of geological objects.

In this paper, we use the Symmetric Hyperbolic Thermodynamically Compatible (SHTC) model to study small amplitude waves in a layered medium containing a porous layer for temperature-varying porosity. The purpose of the study is to reveal the features of the behavior of reflected waves from a porous layer, saturating liquid in which undergoes a phase transition from a solid to a

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liquid state (in this case, porosity increases). Such features will help, for example, outline approaches to the development of geophysical methods for searching for and monitoring the development of natural accumulations of gas hydrates.

As a basis for such consideration, we choose the thermodynamically compatible model developed in [1–4]. This choice is due to the flexibility of the model, which allows generalizations to the case of a multiphase saturating liquid and finite deformations of the skeleton, the possibility of taking into account phase transformations, and so on. The use of the generally accepted Biot approach for modeling porous media [5–7] is problematic, due to the difficulties that arise when trying to generalize Biot's model to describe the phenomena mentioned above. The theory of SHTC systems of conservation laws [8–10], applied to the modeling of multiphase media, makes it possible to design a mathematically well-posed hyperbolic model for the flow of a multiphase compressible mixture in a deformable porous skeleton, which satisfies the laws of nonequilibrium thermodynamics [1–4]. Note that in the case of small deformations, the SHTC model of a porous medium saturated with a compressible liquid qualitatively gives the same results in describing wavefields as the Biot's model [1].

The rest of the paper is organized as follows. Section 2 formulates the general equations of the SHTC model of a porous medium in the case of finite deformations and its linearized version for the case of small deformations. Section 3 presents a brief description of the finite difference scheme on a staggered grid, and Sect. 4 presents a numerical test problem that demonstrates the features of wave propagation in a layered medium for different porosities, which can vary depending on temperature.

2 Symmetric Hyperbolic Thermodynamically Compatible System of Deformed Saturated Porous Medium

2.1 A General Master System for Processes in a Deformed Saturated Porous Medium

Consider a deformable porous medium saturated with the compressible fluid. We restrict ourselves to single entropy approximation [1], which is admissible for small variations in the phase temperatures. The governing PDEs of the general SHTC model in the case of finite strains and in the single entropy approximation are read as

$$\frac{\partial \rho v^i}{\partial t} + \frac{\partial (\rho v^i v^k + \rho^2 E_\rho \delta_{ik} + w^i E_{w^k} + \rho A_{ki} E_{A_{kj}})}{\partial x_k} = 0, \tag{1}$$

$$\frac{\partial A_{ik}}{\partial t} + \frac{\partial A_{im} v^m}{\partial x_k} + v^j \left(\frac{\partial A_{ik}}{\partial x_j} - \frac{\partial A_{ij}}{\partial x_k} \right) = -\frac{\psi_{ik}}{\theta}, \tag{2}$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho v^k}{\partial x_k} = 0, \tag{3}$$

$$\frac{\partial \rho c_1}{\partial t} + \frac{\partial (\rho c_1 v^k + \rho E_{w^k})}{\partial x_k} = 0, \tag{4}$$

$$\frac{\partial w^k}{\partial t} + \frac{\partial (w^l v^l + E_{c_1})}{\partial x_k} + v^l \left(\frac{\partial w^k}{\partial x_l} - \frac{\partial w^l}{\partial x_k} \right) = -\frac{\lambda_k}{\theta_2}, \tag{5}$$

$$\frac{\partial \rho \alpha_1}{\partial t} + \frac{\partial \rho \alpha_1 v^k}{\partial x_k} = -\frac{\rho \varphi}{\theta_1}, \tag{6}$$

$$\frac{\partial \rho s}{\partial t} + \frac{\partial \rho s v^k}{\partial x_k} = \frac{\rho}{\theta E_s} \psi_{ik} \psi_{ik} + \frac{\rho}{\theta_1 E_s} \varphi^2 + \frac{\rho}{\theta_2 E_s} \lambda_k \lambda_k \geq 0. \tag{7}$$

Here (1) is the momentum conservation law for the entire porous medium, (2) is the evolution equation for the distortion (elastic deformation gradient), (3) is the mass conservation law for the entire medium, (4) is the mass conservation law for the saturating fluid, (5) is the equation for the relative velocity, (6) is the balance equation for the fluid volume fraction and (7) is the entropy balance law. The following state variables are used: α_1 is the volume fraction of saturating fluid ($\alpha_2 = 1 - \alpha_1$ - volume fraction of deformable skeleton), ρ_1, ρ_2 are the mass densities of the fluid and the skeleton, respectively, $\rho = \alpha_1 \rho_1 + \alpha_2 \rho_2$ is the mass density of the mixture, $c_1 = \alpha_1 \rho_1 / \rho$ is the mass fraction of the fluid ($c_2 = 1 - c_1$ - the mass fraction of the skeleton), $v^k = c_1 v_1^k + c_2 v_2^k$ is the mixture velocity, v_1^k, v_2^k are velocities of fluid and skeleton, respectively, $w_k = v_1^k - v_2^k$ is the relative velocity and s is the entropy of the mixture.

The main closing relation for system (1)–(7) is the generalized internal energy E which we take in the form

$$E = E_1(c_1, |\mathbf{w}|) + E_2(\alpha_1, c_1, \rho, s) + E_3(c_1, \rho, s, A_{ik}). \tag{8}$$

The kinetic energy of the relative motion E_1 is defined as

$$E_1(c_1, |\mathbf{w}|) = \frac{1}{2} c_1 (1 - c_1) \rho w^j w^j. \tag{9}$$

The energy of volumetric deformation E_2 is defined as

$$E_2(\alpha_1, c_1, \rho, s) = c_1 e_1(\rho_1, s) + c_2 e_2(\rho_2, s) = c_1 e_1 \left(\frac{\rho c_1}{\alpha_1}, s \right) + c_2 e_2 \left(\frac{\rho c_2}{\alpha_2}, s \right). \tag{10}$$

The shear energy E_3 depends on the distortion of the entire solid-fluid mixture element and is read as

$$E_3 = \frac{1}{8} c_2 c_s^2 \left(tr(\mathbf{g}^2) - 3 \right), \tag{11}$$

where c_s is the shear velocity of sound of the solid skeleton, and $\mathbf{g}$ is the normalized Finger strain tensor: $\mathbf{g} = \mathbf{G}(det\ \mathbf{G})^{-1/3}$, $\mathbf{G} = \mathbf{A}^T\mathbf{A}$.

There are three dissipative source terms in the above system corresponding to shear stress relaxation (Eq. (2)), relative velocity relaxation (Eq. (5)), and phase pressure relaxation to a common value (Eq. (6)). There is a source term in the entropy Eq. (7), which describes the growth of entropy due to described above relaxation processes. The dissipative source terms are proportional to thermodynamic forces:

$$\psi_{ik} = E_{A_{ik}}, \quad \lambda_k = E_{w_k}, \quad \phi = E_\alpha,$$

and parameters $\theta, \theta_1, \theta_2$ characterize the rate of relaxation and can be a functions of state variables.

Using the chosen internal energy, the thermodynamic forces can be calculated as

$$E_{\alpha_1} = \frac{p_2 - p_1}{\rho}, \quad p = \rho^2 E_\rho = \alpha_1 p_1 + \alpha_2 p_2, \quad p_i = \rho_i^2 \frac{\partial e_i}{\partial \rho_i}, \ (i = 1, 2) \tag{12}$$

$$\frac{\partial E}{\partial \mathbf{A}} = \frac{c_s^2}{2}\mathbf{A}^{-T}\left(\mathbf{g}^2 - \frac{tr(\mathbf{g}^2)}{3}\delta_{ij}\right), \quad \sigma_{ij} = -\frac{\rho c_s^2}{2}\left(g_{ik}g_{kj} - \frac{1}{3}g_{lk}g_{kl}\delta_{ij}\right), \tag{13}$$

$$E_{c_1} = e_1 + \frac{p_1}{\rho_1} - e_2 - \frac{p_2}{\rho_2} + (1 - 2c_1)\frac{w^i w^i}{2} - c_s^2\left(tr(\mathbf{g}^2) - 3\right), \tag{14}$$

$$E_{w^i} = c_1 c_2 w^i, \quad E_s = T = c_1\frac{\partial e_1}{\partial s} + c_2\frac{\partial e_2}{\partial s}. \tag{15}$$

Equations (1)–(7) can be transformed to a symmetric hyperbolic system and satisfy the thermodynamic laws - energy conservation and entropy growth [1]. They can be used to simulate complex processes in a porous medium, including fluid flows in a deformable medium accompanied by temperature variations.

2.2 Linear System for Modeling the Propagation of Small Amplitude Waves

We are interested in modeling small amplitude wavefields, and for this purpose it is convenient to linearize (1)–(7) under the assumption of small deformations and small temperature variations. We also assume instantaneous pressure relaxation, which is natural to assume for a small pore space, since the phase pressures are equalized due to the propagation and reflection of sound waves in the pores. After linearization we come to the hyperbolic system of linear PDEs written in terms of velocities, relative velocities, pressure and shear stress:

$$\rho_0 \frac{\partial V^i}{\partial t} + \frac{\partial P}{\partial x_i} - \frac{\partial \Sigma_{ik}}{\partial x_k} = 0, \tag{16}$$

$$\frac{\partial W^k}{\partial t} + \left(\frac{1}{\rho_1^0} - \frac{1}{\rho_2^0}\right) \frac{\partial P}{\partial x_k} = -\frac{c_1^0 c_2^0}{\theta_2} W^k, \tag{17}$$

$$\frac{\partial P}{\partial t} + K \frac{\partial V^k}{\partial x_k} + \frac{\alpha_1^0 \alpha_2^0}{\rho_0} \left(\rho_2^0 - \rho_1^0\right) K \frac{\partial W^k}{\partial x_k} = F, \tag{18}$$

$$\frac{\partial \Sigma_{ik}}{\partial t} - \mu \left(\frac{\partial V^i}{\partial x_k} + \frac{\partial V^k}{\partial x_i} - \frac{2}{3}\delta_{ik} \frac{\partial V^j}{\partial x_j}\right) = -\frac{\Sigma_{ik}}{\tau}. \tag{19}$$

Here V^i, W^k, P, Σ_{ik} are, respectively, small perturbations of the velocity, relative velocity, pressure, and shear stress tensor of the steady unstressed state. $K = (\alpha_1^0 K_1^{-1} + \alpha_2^0 K_2^{-1})^{-1}$ is the bulk modulus of the mixture, $\mu = \alpha_2^0 \rho_2^0 c_s^2$ is the shear modulus of the mixture (it is assumed that the shear modulus in the fluid is equal to zero). $K_1 = \rho_1^0 \frac{\partial p_1}{\partial \rho_1}|_{\rho_1=\rho_1^0}$, $K_2 = \rho_2^0 \frac{\partial p_2}{\partial \rho_2}|_{\rho_2=\rho_2^0}$ are the bulk moduli of fluid and solid, respectively. The index 0 denotes the initial unperturbed values of the state variables in the stationary state.

Equations (17) and (19) contain dissipation mechanisms corresponding to interfacial friction and shear stress relaxation, respectively. The source term $F = F(x,t)$ presented in (18) is designed to generate waves in the medium.

We are interested in studying the properties of wavefields depending on temperature. Although in (16)–(19) the temperature is not explicitly represented, its influence can be seen from the change in the coefficients depending on the temperature. Of greatest interest is the change in the wave properties of the medium for the case of phase changes in the saturating liquid during its transformation from a solid to a liquid state. Examples of such phenomena are the thawing of permafrost and the decomposition of gas hydrates. Apparently, in this case, the temperature dependence of the coefficient of interfacial friction and initial porosity can have the highest influence on the properties of wave fields. Below we will numerically study only the effect of changing porosity on wavefields and see that this effect is significant.

3 Finite Difference Method

The numerical method that we use for simulations is based on the staggered grid finite difference scheme [11,12]. We consider the two-dimensional case and introduce new notations for the coordinates $x_1 = x$, $x_2 = y$ and the state variables $V_1, = V_x$, $V_2 = V_y$, $W_1 = W_x$, $W_2 = W_y$, $\Sigma_{11} = \Sigma_{xx}$, $\Sigma_{22} = \Sigma_{yy}$, $\Sigma_{12} = \Sigma_{xy}$. In the space and time domain (t,x,y) let us introduce a grid with the integer nodes $t^n = n\Delta t$, $x_i = i\Delta x$, $y_j = j\Delta y$ and the half-integer nodes $t^{n+1/2} = (n+1/2)\Delta t$, $x_{i+1/2} = (i+1/2)\Delta x$, $y_{j+1/2} = (j+1/2)\Delta y$, where Δt, Δx, and Δy denote grid intervals in time and space.

For a discrete function $f_{i,j}^n = f(t^n, x_i, y_j)$ let us define central difference operators

$$D_t[f]_{i,j}^n = \frac{(f)_{i,j}^{n+1/2} - (f)_{i,j}^{n-1/2}}{\Delta t}, \qquad A_t[f]_{i,j}^n = \frac{(f)_{i,j}^{n+1/2} + (f)_{i,j}^{n-1/2}}{2}, \tag{20}$$

and fourth-order central operators (Levander stencil)

$$D_x[f]^n_{i,j} = \frac{1}{\Delta x}\left\{\frac{9}{8}\left((f)^n_{i+1/2,j} - (f)^n_{i-1/2,j}\right) - \frac{1}{24}\left((f)^n_{i+3/2,j} - (f)^n_{i-3/2,j}\right)\right\}, \tag{21}$$

$$D_y[f]^n_{i,j} = \frac{1}{\Delta y}\left\{\frac{9}{8}\left((f)^n_{i,j+1/2} - (f)^n_{i,j-1/2}\right) - \frac{1}{24}\left((f)^n_{i,j+3/2} - (f)^n_{i,j-3/2}\right)\right\}. \tag{22}$$

Finite-difference scheme on a staggered grid is based on the finite-volume discretization method [13], which is used for systems of equations arising from physical conservation laws. To this end, we define medium parameters and wavefield components at different time-space grid nodes. In the method being used, we determine the state variables of the medium at different nodes of the space-time grid. It is assumed that the material parameters are constant within each grid cell $[x_{i-1/2}, x_{i+1/2}] \times [y_{j-1/2}, y_{j+1/2}]$ with possible discontinuities along the grid lines. The mixture velocities V_x, V_y and the relative velocities W_x, W_y are defined at points numbered $(i+1/2, j)$, $(i, j+1/2)$ as $(V_x)^n_{i+1/2,j}$, $(V_y)^n_{i,j+1/2}$, $(W_x)^n_{i+1/2,j}$, $(W_y)^n_{i,j+1/2}$. The pressure and the normal components of the deviatoric stress are defined at points (i,j) as $(P)^{n+1/2}_{i,j}$, $(\Sigma_{xx})^{n+1/2}_{i,j}$, $(\Sigma_{yy})^{n+1/2}_{i,j}$, and the shear stress is defined at points $(i+1/2, j+1/2)$ as $(\Sigma_{xy})^{n+1/2}_{i+1/2,j+1/2}$. The details can be seen on Fig. 1.

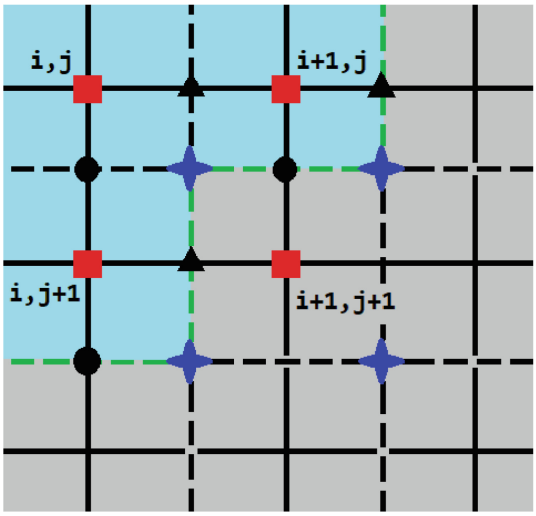

Fig. 1. The relative position of the wavefield components on the staggered grid near the medium interface: red square (integer i and j) - $\Sigma_{xx}, \Sigma_{yy}, P$; blue star (half-integer i and j) - Σ_{xy}; black triangle (half-integer i, integer j) - V_x, W_x; black circle (integer i, half-integer j) - V_y, W_y. The green dashed line is the interface on the staggered grid. (Color figure online)

The constructed finite difference scheme reads as

$$D_t[V_x]^{n-1/2}_{i+1/2,j} = -\left\langle 1/\rho^0 \right\rangle_{i+1/2,j} D_x[P]^{n-1/2}_{i+1/2,j} + \left\langle 1/\rho^0 \right\rangle_{i+1/2,j} \left(D_x[\Sigma_{xx}]^{n-1/2}_{i+1/2,j} + D_y[\Sigma_{xy}]^{n-1/2}_{i+1/2,j} \right), \tag{23}$$

$$D_t[V_y]^{n-1/2}_{i,j+1/2} = -\left\langle 1/\rho^0 \right\rangle_{i,j+1/2} D_y[P]^{n-1/2}_{i,j+1/2} + \left\langle 1/\rho^0 \right\rangle_{i,j+1/2} \left(D_x[\Sigma_{xy}]^{n-1/2}_{i,j+1/2} + D_y[\Sigma_{yy}]^{n-1/2}_{i,j+1/2} \right), \tag{24}$$

$$D_t[W_x]^{n-1/2}_{i+1/2,j} = -\left\langle 1/\rho_1^0 - 1/\rho_2^0 \right\rangle_{i+1/2,j} D_x[P]^{n-1/2}_{i+1/2,j} - \left\langle c_1^0 c_2^0/\theta_2 \right\rangle_{i+1/2,j} A_t[W_x]^{n-1/2}_{i+1/2,j}, \tag{25}$$

$$D_t[W_y]^{n-1/2}_{i,j+1/2} = -\left\langle 1/\rho_1^0 - 1/\rho_2^0 \right\rangle_{i,j+1/2} D_y[P]^{n-1/2}_{i,j+1/2} - \left\langle c_1^0 c_2^0/\theta_2 \right\rangle_{i,j+1/2} A_t[W_y]^{n-1/2}_{i,j+1/2}, \tag{26}$$

$$D_t[P]^n_{i,j} = -(K)_{i,j} \left(D_x[V_x]^n_{i,j} + D_y[V_y]^n_{i,j} \right) - \left((\rho_2^0 - \rho_1^0)\alpha_1^0 \alpha_2^0 K/\rho^0 \right)_{i,j} \left(D_x[W_x]^n_{i,j} + D_y[W_y]^n_{i,j} \right), \tag{27}$$

$$D_t[\Sigma_{xx}]^n_{i,j} = (\mu)_{i,j} \left(\frac{4}{3} D_x[V_x]^n_{i,j} - \frac{2}{3} D_y[V_y]^n_{i,j} \right) - (1/\tau)_{i,j} A_t[\Sigma_{xx}]^n_{i,j}, \tag{28}$$

$$D_t[\Sigma_{yy}]^n_{i,j} = (\mu)_{i,j} \left(\frac{4}{3} D_y[V_y]^n_{i,j} - \frac{2}{3} D_x[V_x]^n_{i,j} \right) - (1/\tau)_{i,j} A_t[\Sigma_{yy}]^n_{i,j}, \tag{29}$$

$$D_t[\Sigma_{xy}]^n_{i+1/2,j+1/2} = \{\mu\}_{i+1/2,j+1/2} \left(D_x[\Sigma_y]^n_{i+1/2,j+1/2} + D_y[V_x]^n_{i+1/2,j+1/2} \right) - \{1/\tau\}_{i+1/2,j+1/2} A_t[\Sigma_{xy}]^n_{i+1/2,j+1/2}, \tag{30}$$

where the parameters of the medium on the staggered grid are defined as volume arithmetic averaging

$$\langle f \rangle_{i+1/2,j} = (f_{i,j} + f_{i+1,j})/2, \qquad \langle f \rangle_{i,j+1/2} = (f_{i,j} + f_{i,j+1})/2, \tag{31}$$

or harmonic averaging [14]

$$f_{i+1/2,j+1/2} = \left[\frac{1}{4} \left(\frac{1}{f_{i,j}} + \frac{1}{f_{i+1,j}} + \frac{1}{f_{i,j+1}} + \frac{1}{f_{i+1,j+1}} \right) \right]^{-1}. \tag{32}$$

4 Numerical Test Problem

Let us consider a simple model of a medium consisting of a "gas hydrate" (a substance that changes from a solid to a liquid when the temperature rises) layer inside a homogeneous elastic medium. The choice of such a simplified model is due to the desire to reveal the main features of the behavior of reflected waves from a layer of gas hydrates. The presence of specific properties of wave behavior can help formulate prognostic signs of the existence of gas hydrates in the fields of seismic waves, as well as outline approaches to the development of geophysical

methods for searching and analyzing the evolutionary processes of gas hydrate deposits.

The velocities of seismic waves in a homogeneous medium were selected based on the plot of velocities characteristic of gas hydrates as a function of temperature [15] and are presented in Table 1.

Table 1. Material parameters of the media.

State	Parameter	Notation	Value	Unit
Surrounding medium	Longitudinal sound velocity	V_p	2400	m/s
	Shear sound velocity	V_s	1800	m/s
	Density	ρ_2	2500	kg/m^3
Gas hydrate *Solid state*	Longitudinal sound velocity	V_p	3800	m/s
	Shear sound velocity	V_s	2400	m/s
	Density	ρ_2	2500	kg/m^3
Gas hydrate *Liquid state*	Longitudinal sound velocity	V_p	1300	m/s
	Shear sound velocity	V_s	800	m/s
	Density	ρ_1	1040	kg/m^3
Dissipative parameters	Interphase friction	$c_1^0 c_2^0/\theta_2$	$3.36 \cdot 10^{-7}$	s^{-1}
	Relaxation time	τ	10^{-4}	s

Table 1 lists the parameters that make it possible to describe a layer of gas hydrates as a poroelastic medium consisting of a mixture of solid and liquid (viscous liquid) phases, while the host medium is considered as a pure elastic medium.

Depending on the depth, temperature and pressure inside the formation, gas hydrates can be either frozen (solid hydrate state) or decomposing if they are outside their stable state zone, for example, when the temperature rises. In the case of frozen gas hydrates, they can be considered as an elastic medium by setting a fluid volume fraction α_1^0 to 0 in Eq. (16)–(19). When gas hydrate melt, the porosity of a layer $\phi = \alpha_1^0 = 1 - \alpha_2^0$ increases until the value of pure liquid (gaseous) state $\phi = 1$. Below one can see the results of numerical simulations for the following parameters of porosity inside the gas hydrate layer: $\phi = 0, \phi = 0.2, \phi = 0.5, \phi = 0.7$. The calculations were carried out for the region (500 m $\times$ 500 m) with a horizontal layer on the depth (150 m, 250 m). The wavefield is excited by a source of the type of volumetric expansion $F(x, y, t) = \delta(x_0, y_0) f(t)$ (δ - Dirac's delta function, localizing the source in point (x_0, y_0)) in (18) at a depth of 30 m. The time function is given by Ricker's wavelet $f(t) = (1 - \omega^2(t - t_0)^2/2) exp[-\omega^2(t - t_0)^2/4]$ with frequency $f_0 = 1$ KHz and pulse delay $t_0 = 2/f_0$. The seismogram was recorded along a vertical observation line passing through the source with a vertical interval between receivers 1 m.

The results of numerical calculations are shown in Fig. 2, 3, 4, 5 and 6. Figures 2, 3, 4 and 5 show seismograms of the magnitude of the mixture velocity

vector, recorded along the vertical observation line passing through the source with an interval 1 m between receivers up to time 0.25 s for different porosities. Figure 6 shows wavefield traces superimposed on each other for the magnitude of mixture velocity vector, recorded by the receiver at a depth of 30 m in the time interval 0.06–0.25 s for various values of the porosity: $\phi = 0, \phi = 0.2, \phi = 0.5, \phi = 0.7$.

For the convenience of classifying the emerging types of waves in the figures, we use the following notation. We denote the P-waves by the letter P, and the S-waves by the letter S. We also denote the reflected waves by the subscripts r and the transmitted waves by t.

From a comparison of the traces for different porosity values in the gas hydrate layer, it can be seen that the greater the porosity, the higher the amplitude of the reflected wave from the upper boundary of the gas hydrate layer (PPr, PSr, SSr). The time of arrival of these waves is obviously the same. We observe a completely different picture for waves reflected from the lower boundary of the gas hydrate layer ($PPtPrPt, PPtSrPt$). For these waves, strong dispersion is observed, which occurs due to the passage of the wave through the porous layer. With an increase in porosity, the velocity increases proportionally, while the amplitude of the waves does not change significantly for the P-wave reflected from the lower layer. For the S-wave reflected from the lower layer, a noticeable increase in amplitude is observed with increasing porosity.

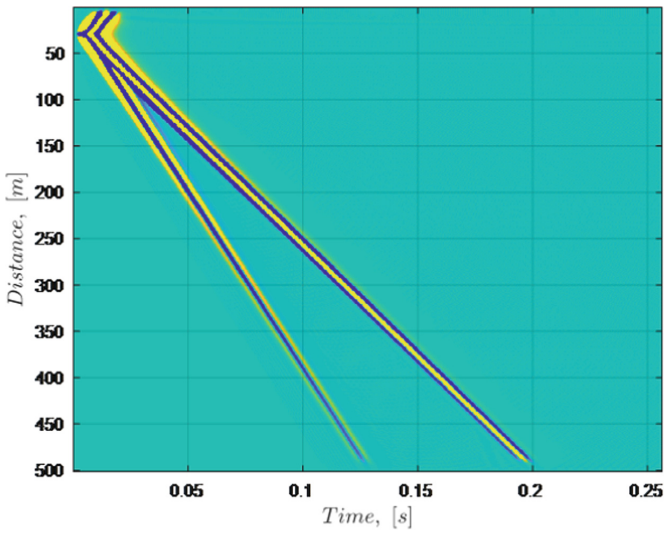

Fig. 2. Seismograms of the magnitude of the mixture velocity vector, recorded along the vertical observation line passing through the source with an interval 1 m between receivers up to time 0.25 s for porosity $\phi = 0$.

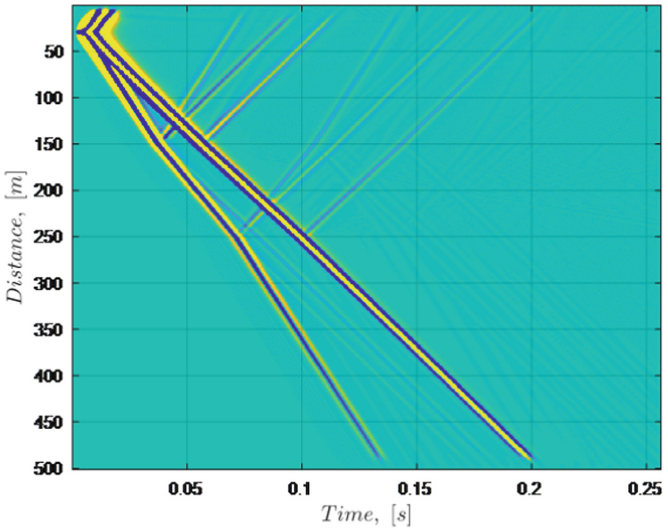

Fig. 3. Seismograms of the magnitude of the mixture velocity vector, recorded along the vertical observation line passing through the source with an interval 1 m between receivers up to time 0.25 s for porosity $\phi = 0.2$.

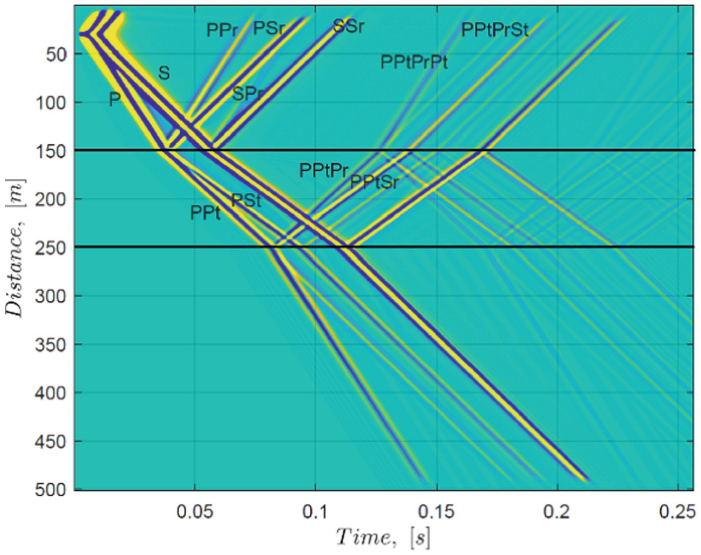

Fig. 4. Seismograms of the magnitude of the mixture velocity vector, recorded along the vertical observation line passing through the source with an interval 1 m between receivers up to time 0.25 s for porosity $\phi = 0.5$.

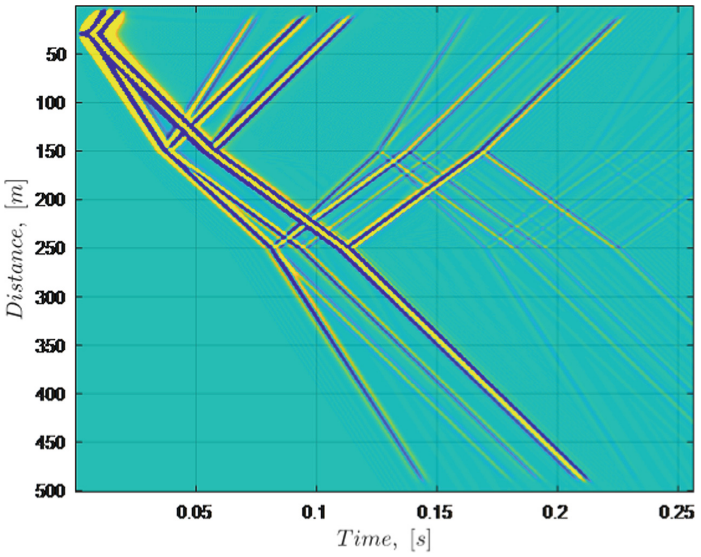

Fig. 5. Seismograms of the magnitude of the mixture velocity vector, recorded along the vertical observation line passing through the source with an interval 1 m between receivers up to time 0.25 s for porosity $\phi = 0.7$.

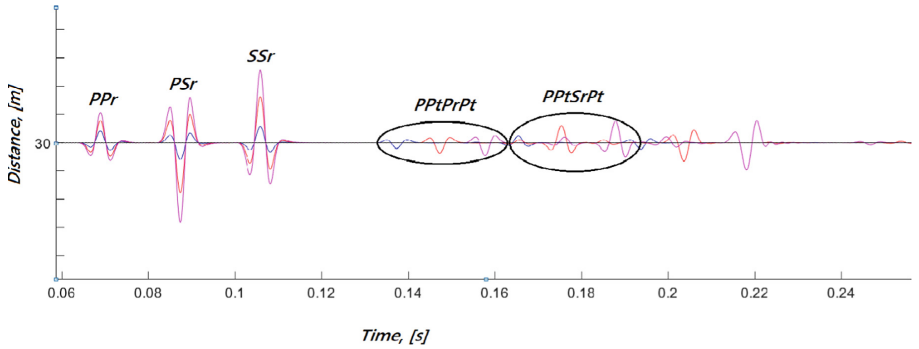

Fig. 6. Traces for the magnitude of the mixture velocity vector recorded by the receiver at a depth of 30 m in the time interval 0.06–0.25 s: black - $\phi = 0$, blue - $\phi = 0.2$, red - $\phi = 0.5$, magenta - $\phi = 0.7$. (Color figure online)

5 Conclusions

A Symmetric Hyperbolic Thermodynamically Compatible (SHTC) model of saturated porous medium is applied to the study of wave propagation in a medium contained a porous layer. The general SHTC model for the case of finite deformation of saturated porous medium is formulated and its linearization for the

modeling of small amplitude waves is presented. The efficient finite difference method on staggered grid is developed and applied to solving a two-dimensional test problems. The features of wave propagation with a change in porosity, which may be a consequence of a change in temperature, are studied. It is numerically shown that for waves reflected from the upper boundary of the porous layer, amplitude variations are observed with a change in porosity, and for waves reflected from the lower boundary of the layer, a strong dispersion is observed depending on porosity. These features of wavefields can be used as the basis for the development of methods for monitoring the evolution of natural accumulations of gas hydrates or permafrost thawing. Further research will include studying the effect of interfacial friction and shear stress relaxation time, which change with temperature, on the behavior of wavefields.

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Optimal Time-Step for Coupled CFD-DEM Model in Sand Production

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Abstract. The coupled Computational Fluid Dynamics and Discrete Element Method (CFD-DEM) is a useful tool for modeling the dynamics of sand production that occurs in oil and gas reservoirs. To perform accurate, physically relevant and efficient calculations, the optimal size of the simulation time-step should be selected. In this study, we investigate the selection of an appropriate time-step interval between CFD and DEM models in sand production simulations. The CPU time, speedup and root mean squared relative error of the obtained results are examined to compare the sand production phenomenon at different coupling numbers. Most of the results including the final sand production rate, bond number and bond ratio indicate that the simulations with coupling numbers of $N = 10$ and $N = 100$ produce more accurate results. Moreover, these outcomes demonstrate significant improvements in terms of acceleration of the modeling process.

Keywords: Time-step · Sand production · CFD-DEM coupling

1 Introduction

Sand production is the source of many issues in the oil industry, and it has a negative impact on well completion. Plugging of lines during the perforations or production operations, wellbore instability, or the damage of a horizontal well in poorly consolidated formations tends to have environmental effects that may have additional remedial and clean-up operational costs. Moreover, it may impact the erosion of pipelines and surface facilities, which are a few issues due to sand production. Sanding prevention in wells through mechanical means is expensive and results in low output and injectivity. As a result, sand production management and modeling should be implemented early before well completions to save money [27].

Modeling the sand production process is challenging because the characteristics of fluids and sand particles should be thoroughly assessed, including particle-particle, particle-fluid, and particle-wall interactions. Recently, coupling the Computational Fluid Dynamics (CFD) and the Discrete Element Method

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(DEM) system has been adopted as a promising modeling approach for particle-fluid flow problems commonly used to describe sand production phenomena [14,19].

The CFD-DEM combines the Eulerian-Lagrangian technique for modeling fluid-particle systems [24]. The Discrete Element Method (DEM) [7], which uses Newton's law to trace the movement and position of individual particles, is employed to calculate the solid phase. The Computational Fluid Dynamics (CFD) [25] models the fluid phase by solving the locally averaged Navier-Stokes equations. In DEM, the equations of motions are solved by explicit numerical integration schemes.

Several numerical coupling schemes are proposed to simulate the particle-fluid interactions. The coupling system is commonly classified into three types: resolved [23], unresolved, and semi-resolved, based on CFD mesh resolution and particle sizes. The CFD mesh resolution is much larger than the particle size in the unresolved coupled system. In comparison, the resolved case is suitable when the CFD mesh resolution is much smaller than the particle size and requires the moving immersed boundary (MIB) or immersed boundary method (IBM) to calculate interphase force. The semi-resolved CFD-DEM coupling is used when the particle size is close to the CFD mesh resolution. The interphase force calculation is determined based on the porosity calculation algorithm [26].

The unresolved approach requires few computational grids; thereby, computational efficiency is higher than resolved and semi-resolved methods and doesn't need integration along the grain boundary. However, one should note that the interphase force accuracy of the unresolved coupling method is lower than semi-resolved and resolved coupling techniques [2].

The correlation between the time-steps of DEM and CFD coupling is essential since the time-step size determines the stability of the numerical schemes. A relatively minor time-step results in precise outcomes, while more significant time-steps increase errors by resulting inaccurate results. Nevertheless, one should note that the simulation time is growing by decreasing the time-step. Therefore, the most favorable time-step to perform accurate and stable simulations should be selected.

This study is extension of the research on the sand production process in the shallow and poorly consolidated formations of the Ustyurt-Buzachi sedimentary basin of Kazakhstani oilfields, located between the Caspian Sea and the Aral Sea [13]. Sanding is common in Cretaceous sandstones, consisting mainly of loose sand and weakly cemented sandstones. The numerical study was conducted based on the experimental laboratory data [17], where the particle size distribution (PSD) was taken from the field data [15,20,21].

In this work, we also focus on numerically exploring the correlation between the time-step of DEM and the time-step of CFD in a coupled system. The optimization of this relationship can result in a reduction of the CPU time for the sand production simulation of the oil and gas reservoir using CFD-DEM model.

2 Numerical Model Formulation

2.1 Model of the Particulate Phase

The discrete element method (DEM) is a computational model for examining the mechanical characteristics of discrete solid particles developed by Cundall and Strack [7]. The DEM technique is frequently used in a variety of scientific domains to look at how granular materials behave, including powders, soils, and rocks. The process replicates the motion and interactions of the particles under various circumstances depicting the particles as distinct and interacting objects. While Newton's second law governs the particle motion, the force-displacement relationships are used to calculate the contact forces between particles. We describe the translational and rotational motion of the particles by using the following equations:

$$m_i \frac{d\mathbf{v}_i}{dt} = \boldsymbol{f}_{pf,i} + \sum_{j=1}^{k_c} (\boldsymbol{f}_{c,ij} + \boldsymbol{f}_{damp,ij}) + m_i \boldsymbol{g} \tag{1}$$

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_{j=1}^{k_c} \boldsymbol{T}_{ij} \tag{2}$$

where m_i is the particle mass, $\mathbf{v_i}$ is the particle translational velocity, $\boldsymbol{\omega_i}$ is the particle angular velocity, I_i is the particle moment of inertia, k_c is the number of particles that interact with other particles, $\boldsymbol{f}_{pf,i}$ is the particle-fluid interaction force, $\boldsymbol{f}_{c,ij}$ and $\boldsymbol{f}_{damp,ij}$ are the contact force and damping force between particles, $\boldsymbol{T}_{ij}$ is the torque acting on particle i by particle j, and $m_i\boldsymbol{g}$ is the gravitational force.

The total particle-fluid interaction force $\boldsymbol{f}_{pf,i}$ acting on a single particle i can be defined as follows:

$$\boldsymbol{f}_{pf,i} = \boldsymbol{f}_{d,i} + \boldsymbol{f}_{\nabla p,i} + \boldsymbol{f}_{\nabla \cdot \boldsymbol{\tau},i} + \boldsymbol{f}_i^{''} \tag{3}$$

where $\boldsymbol{f}_{d,i}$ is the drag force, $\boldsymbol{f}_{\nabla p,i}$ is the pressure gradient force, $\boldsymbol{f}_{\nabla \cdot \boldsymbol{\tau},i}$ is the viscous force and $\boldsymbol{f}_i^{''}$ is the sum of other forces such as virtual mass force, Basset force, Saffman and Magnus lift forces [6].

The contact force $\boldsymbol{f}_{c,ij}$ between particle i and particle j is described by the linear spring-dashpot-slider model [7], which consists of normal (n) and tangential (t) components:

$$\boldsymbol{f}_{c,ij}^{(n)} = -k_n \boldsymbol{\delta}_{n,ij} - \eta_n \boldsymbol{v}_{n,ij} \tag{4}$$

$$\boldsymbol{f}_{c,ij}^{(t)} = -min\left(\mu \boldsymbol{f}_{c,ij}^{(n)}, k_t \boldsymbol{\delta}_{t,ij} + \eta_t \boldsymbol{v}_{t,ij}\right) \tag{5}$$

where $\boldsymbol{\delta_{ij}}$ and $\boldsymbol{v_{ij}}$ are the overlap and relative velocity between particle i and particle j, k is the spring stiffness constant, η is the dashpot damping coefficient, μ is the slider friction coefficient.

2.2 CFD-DEM Coupling

In CFD-DEM [24], the system of locally averaged Navier-Stokes equations are used to calculate the fluid flow in a porous medium. In so-called model A [28], only the porous fraction of the material is occupied by fluid, and the pressure drop is distributed between both the fluid and solid phases:

$$\begin{cases} \frac{\partial \alpha_f}{\partial t} + \nabla \cdot (\alpha_f \boldsymbol{u}) = 0 \\ \frac{\partial (\rho_f \alpha_f \boldsymbol{u})}{\partial t} + \nabla \cdot (\rho_f \alpha_f \boldsymbol{u}\boldsymbol{u}) = -\alpha_f \nabla p + \alpha_f \nabla \cdot \boldsymbol{\tau} + \rho_f \alpha_f \boldsymbol{g} + \boldsymbol{F}_{pf}^A \end{cases} \tag{6}$$

where ρ, $\boldsymbol{u}$, p are the density, dynamic velocity and pressure of fluid, α_f is the fluid volume fraction, $\boldsymbol{\tau} = \mu_f \left((\nabla \boldsymbol{u}) + (\nabla \boldsymbol{u})^T \right)$ is the stress tensor, where μ_f is the fluid dynamic viscosity, $\boldsymbol{F}_{pf}^A = \frac{1}{\Delta V} \sum_{i=1}^{n} (f_{d,i} + f_i'')$ is the volumetric particle-fluid interaction force in a single fluid cell of volume ΔV.

The drag force acting on an individual particle by fluid can be described by Di Felice correlation as follows [8]:

$$\boldsymbol{f}_{d,i} = \left(\frac{1}{8} C_{d,i} \rho_f \pi d_i^2 |\boldsymbol{u_i} - \mathbf{v_i}| (\boldsymbol{u_i} - \mathbf{v_i}) \right) \alpha_i^{2-\chi} \tag{7}$$

where $C_{d,i}$ is the drag coefficient, d_i is the diameter of a particle, $\boldsymbol{u_i}$ is the fluid velocity, $\mathbf{v_i}$ is the particle velocity, χ is the porosity correction factor, $\alpha_i = 1 - \sum_{i=1}^{n} V_{p,i} / \Delta V$ is the void fraction of a cell, where $V_{p,i}$ is the volume of a single particle.

We express the drag coefficient and porosity correction factor by the following empirical correlations:

$$C_{d,i} = \left(0.63 + \frac{4.8}{\sqrt{Re_i}} \right)^2 \tag{8}$$

$$\chi = 3.7 - 0.65 \exp \left(-\frac{(1.5 - \log_{10}(Re_i))^2}{2} \right) \tag{9}$$

where $Re_i = \frac{\rho_f d_i \alpha_i |\boldsymbol{u}_i - \mathbf{v_i}|}{\mu_f}$ is a particle Reynolds number.

2.3 Calculation of the Time-Step

The cfdemSolverPiso solver [16], which is based on Pressure-Implicit with Splitting of Operators (PISO) algorithm [11], solves the Navier-Stokes equations (Eq. 6) numerically with the finite volume method (FVM) taking into account the momentum exchange between fluid and solid phases. In the numerical schemes of the CFD-DEM coupled system, the time step is essential for the convergence of nonlinear problems. Therefore, the optimal time-step should be selected for both systems. In general, a smaller time-step outputs more accurate results, while a larger time-step leads to unstable and unrealistic results. There are two commonly used methodologies to compute the optimal time-step for DEM simulations: the time-step as a function of mass and stiffness [1] and the Rayleigh

time-step [18]. The time-step as a function of mass and stiffness is defined as follows:

$$\Delta t_{ms} \propto \sqrt{\frac{m}{k}} \tag{10}$$

where m and k are the mass and stiffness of a particle.

The Rayleigh time-step is expressed by the following equation:

$$\Delta t_R = \frac{\pi r}{\beta}\sqrt{\frac{\rho}{G}} \tag{11}$$

where r is the particle radius, ρ is the particle density, G is the particle shear modulus, and β is approximated by $\beta = 0.8766 + 0.163\nu$, where ν is the particle Poisson's ratio.

In CFD, the critical time-step can be determined by the Courant-Friedrichs-Lewy (CFL) condition [5]:

$$C = \Delta t \left(\sum_{i=1}^{n} \frac{u_i}{\Delta x_{cfd,i}} \right) \leq C_{max} \tag{12}$$

where C is the Courant number, Δt is the time-step of the CFD simulation, $\Delta x_{cfd,i}$ is the spacial size of a single fluid cell and n defines the number of spacial coordinates (typically, $n = 1$, 2 and 3). In general, C_{max} should be equal to 1 or less to ensure a stable simulation. It depends on the time-integration scheme of the solver. From the physical point of view, the CFL condition implies that the information (flow) should not travel over a single cell in one time-step.

In CFD-DEM coupling simulations, the DEM and CFD time-steps may run consecutive or concurrent regimes, see Fig. 1. In the consecutive regime, the data exchange between the DEM and CFD occurs after each other at the same core. In this case, all cores can be used at all times, which is optimal for effective resource usage. In the concurrent regime, the DEM and CFD calculations run in parallel for the space and occupy different cores at the same coupling time-step [16].

The accuracy and stability of CFD-DEM coupling simulations is determined by the time-step interval between those two distinct models. The relationship between DEM and CFD time-steps are defined by coupling number N, which is described by the following equation:

$$N = \frac{\Delta t_{CFD}}{\Delta t_{DEM}} \tag{13}$$

Typically, the DEM time-step is substantially shorter than the CFD time-step. There can be several DEM time-steps for a single CFD time-step. One can control the simulation time and improve the accuracy of the results by selecting the right value of N.

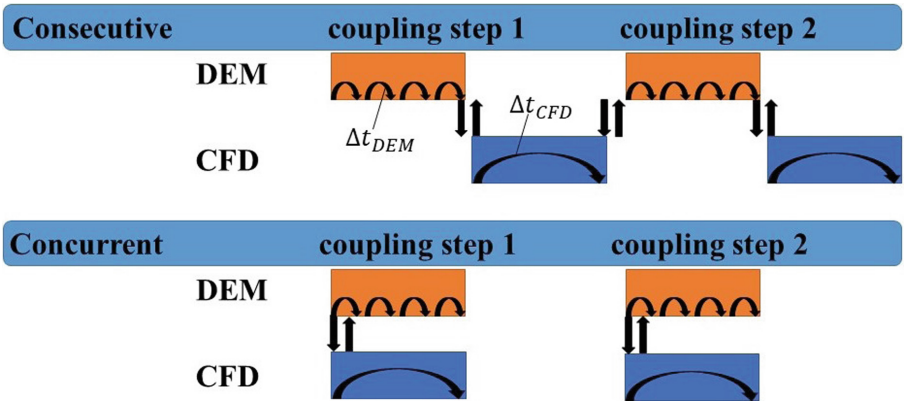

Fig. 1. The consecutive and concurrent time-step regimes in the CFD-DEM coupling (adapted from [16]).

3 Numerical Results

3.1 Numerical Setup of the Simulation

The optimal time-step size of the DEM and CFD ensures efficient and physically relevant simulation results. The DEM time-step size used in this simulation is equal to $\Delta t_{DEM} = 10^{-8}$ s and according to Eq. 11, it is 2.2% of Rayleight critical time-step, which is $\Delta t_R = 4.54 \cdot 10^{-8}$ s. In order to select an optimal coupling number for the CFD-DEM simulations, the following N coupling numbers are taken into consideration: 10, 100 and 1000. The results of those N numbers are compared with $N = 1$, where the DEM and CFD time-step values are the same. The optimal coupling number is selected by comparing the speedup and relative error of the sand production results. Based on those coupling numbers, the CFD simulations are configured with the following time-step values: $\Delta t_{CFD} = 10^{-7}$ s ($N = 10$), $\Delta t_{CFD} = 10^{-6}$ s ($N = 100$) and $\Delta t_{CFD} = 10^{-5}$ s ($N = 1000$), respectively. According to the CFL condition (Eq. 12), these CFD time-step values are within an acceptable range, since the maximum Courant number of $0.66 \cdot 10^{-6}$ is much less than 1.

In the sand production model, the numerical sample is initially prepared using only DEM modeling since it includes only a solid phase. The process is broken down into 3 distinct stages, namely: particle generation, compression and perforation. The particle generation involves creating new particles in the simulation environment and defining their shape and material properties. At the compression stage, the particles are compressed under a stress that corresponds to the experimental conditions. The numerical sample is then perforated vertically in the center. Afterwards, the sand production itself is modeled using CFD-DEM coupling, since it is a complex phenomenon that includes solid and fluid phases.

The coupling geometry is made up of two distinct DEM and CFD geometries, which should have the same size to ensure stable simulation. In the particle generation stage, the DEM geometry is constructed by 18 mm solid planes in a cuboid form, in which the spherical particles were initially created and contained for further simulation stages. The particle size distribution (PSD) and material parameters of the particles are provided in Table 1 and Table 2, respectively.

Table 1. Particle size distribution (PSD) of the simulated particles.

Mass fraction	0.058	0.075	0.088	0.1216	0.2264	0.1705	0.121	0.1395
Diameter, mm	0.3	0.36	0.4	0.44	0.5	0.55	0.6	0.71

Table 2. Material parameters of the simulated particles.

Parameter	
Density, kg/m^3	2605
Young's modulus, Pa	$2 \cdot 10^{10}$
Poisson's ratio	0.3
Restitution coefficient	0.8
Friction coefficient	0.2
Surface energy, J/m^2	60
Particle number	33 750

We use the same PSD and material characteristics as in works of [12,13] to supplement their investigations on the triaxial compression test and sand production phenomenon of unconsolidated reservoir sandstone using the coarse-graining methods in the modified JKR model [22]. This study focuses on the coarse-graining method for polydisperse particles with coarse-graining factor (k_{cg}) of 2. The initial particle size is doubled and the material properties of the particles are scaled accordingly. Therefore, the modeling applied with coarse-graining methods is also accelerated.

In the compression stage, a stress of 1 MPa, which is applied from the top plate to compress the particles in the cell, maintains the porosity of the sample at 42%. After the compression, the modified JKR is applied to create the bonds between particles. The numerical sample is then perforated in the center with a penetrometer, which results in breaking the bonds in perforation locations. After removing the penetrometer from the sample, we initiate the sand production process with the fluid injection by simulating the CFD-DEM coupling. The hole size for the sand production in the DEM model equals to 2.8 mm.

The geometry of the coupling is illustrated in Fig. 2a. The numerical sample size has length of L = 18 mm and height h = 8.82 mm. The CFD domain is segmented into 12x12x6 cells in xyz directions. The particles are considerably

smaller than the dimensions of a single CFD cell, which is capable of accommodating several particles. Hence, the size of the cell in all three directions meets the criteria for the unresolved case, as per the equation below [4]:

$$\frac{\Delta x_{cfd}}{\bar{d}_p} > 3 \tag{14}$$

where $\bar{d}_p$ is the particle average diameter.

The boundary conditions of the model are demonstrated in Fig. 2b. The fluid with velocity of 10^{-4} m/s is injected from two planes which are normal to y-axis (green color). The rest of the planes are set to cyclic boundary conditions (gray color). The pressure exerted on the top and bottom holes is equal to atmospheric pressure (red color). The initial conditions of the model are as follows: $U(0) = 0$ and $P(0) = 0$. The CFD-DEM simulations were performed using the CFDEM coupling tool [9], which integrates the DEM commercial software (Aspherix 6.0) [16] and the CFD open-source software OpenFOAM [3]. The simulations were executed on the high-performance computing (HPC) system equipped with an Intel(R) Xeon(R) Gold 6230R CPU @ 2.10 GHz containing 52 cores. Each case of the coupling number is simulated using 4 cores with parallel computing in 4x1x1 decomposition along the x, y and z axes.

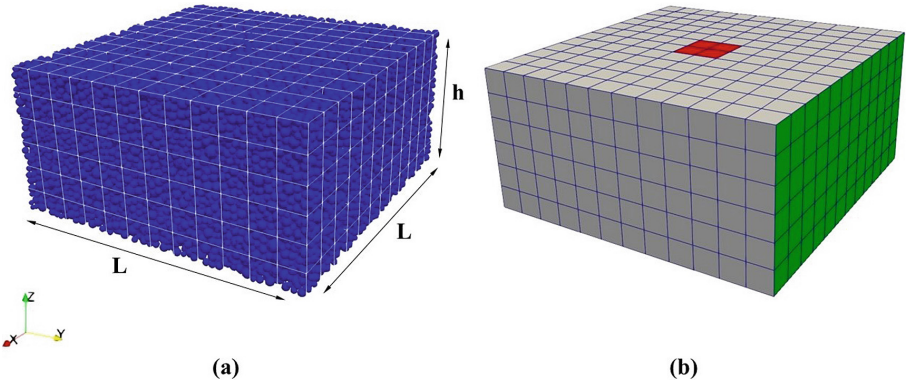

Fig. 2. (a) Geometry and (b) boundary conditions of the model. P = const is in the red zone, U = const is in the green zone, and periodic boundaries is in the grey zone. (Color figure online)

3.2 Analysis of Time-Step

The simulation time for all cases is 0.04 s, in which the sand production become in transient behavior. Figure 3 shows the snapshots of the flow streamlines with fluid velocity in the background and particle velocity in the numerical sample at 0.005 s, 0.02 s, and 0.04 s from the initial condition. At the beginning, we observe an increased fluid velocity at the perforation locations, which leads to

intense mobilization of sand towards the top hole. At t = 0.02 s, the velocity of the fluid decreases significantly, resulting in a deceleration of the sand production rate. At the final time ($t = 0.04$ s), the fluid flow reaches a stationary flow condition, with streamlines being uniformly distributed throughout the sample. As a consequence, there is no occurrence of sand production at this time.

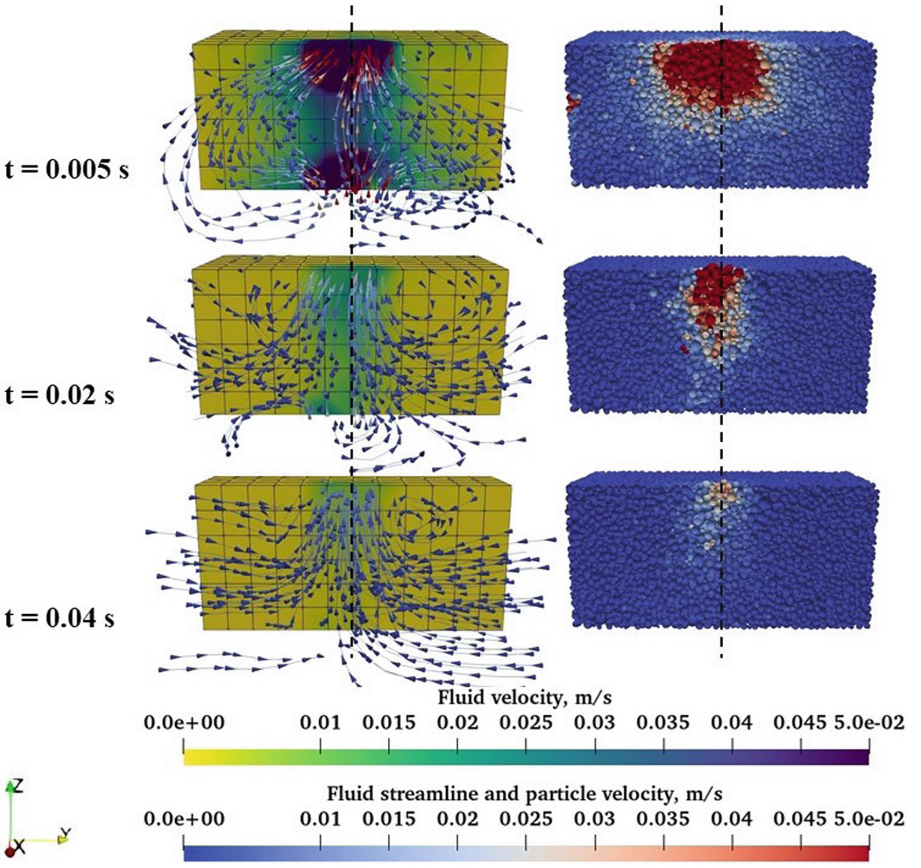

Fig. 3. Flow streamlines with the fluid velocity background and particle velocity.

Figure 4 demonstrates the comparison of cumulative sand production at $N = 1$, 10, 100 and 1000 cases. During the intensive sand production, which is continued from the beginning until 0.005 s, almost a similar amount of sand is produced in all cases. However, in the ranges of gradual (0.005 s–0.02 s) and transient (0.02 s–0.04 s) sand production, the curves become slight different. For instance, the most difference is observed when the simulations are performed at $N = 1000$ coupling number. In that case, we observe an increase in cumulative sand production in the gradual regime, and a decrease in the transient behavior

compared to $N = 1$ coupling number. Although the sand production of $N = 10$ and $N = 100$ is slightly less than $N = 1$, the curves of those coupling numbers are in a similar pattern. The most excellent results are observed at $N = 100$, where the sand production rate and curve pattern are relatively similar to $N = 1$ throughout the entire simulation time.

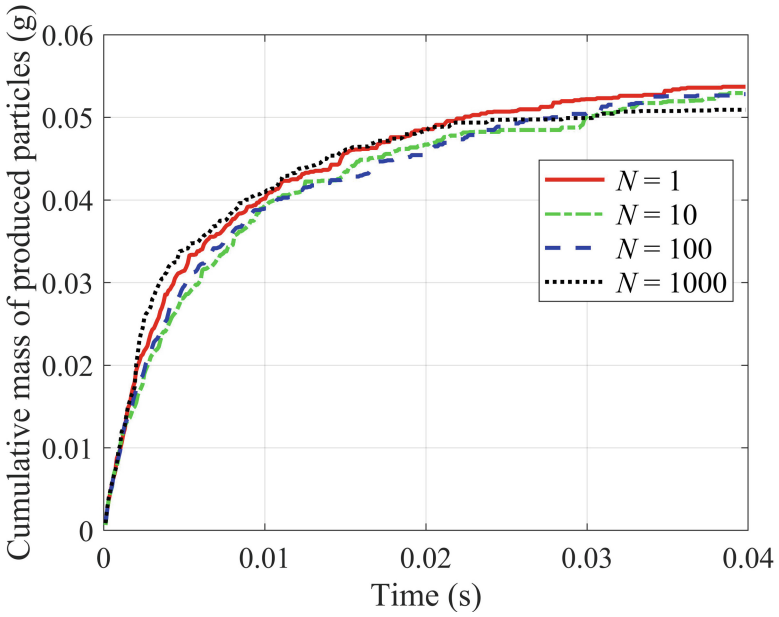

Fig. 4. Comparison of cumulative sand production at $N = 1$, 10, 100 and 1000.

The effect of the coupling numbers on bonding behavior of the particles can be better understood by comparing the bond number and bond ratio in the sample. The cementation of the numerical sample is represented by utilizing the modified JKR contact model [22], in which the particles are cohesively bonded to each other. The bond number shows all existing bonds between particles in the sample. It is possible that the particles might be in contact with other particles, but are not bonded. This usually occurs when the bonds are broken by a force acting on the sample. Particles that are not bonded to each other are modeled by the Hertz contact model [10]. The bond ratio describes the ratio of the bonded particle number to the total number of contacts in the sample. Figure 5a demonstrates the total number of bonds that exist between particles of the coupling numbers $N = 1$, $N = 10$, $N = 100$ and $N = 1000$. At the initial condition all cases have $1.34 \cdot 10^5$ bonds in total. In the intensive sand production regime, the bonds reduced dramatically. As flow becomes stationary, no new breakage of bonds occurs in the sample. The bond numbers of N =10 and $N = 100$ show similar pattern throughout the simulation finishing at about

$1.21 \cdot 10^5$ bonds. This is just above the $N = 1$ results, which bond number equals to $1.206 \cdot 10^5$ at the final time. The $N = 1000$ case loses a drastic number of bonds with intensive sand production and reaches $1.192 \cdot 10^5$ bonds at the end. Figure 5b shows the bond ratio in the sample of the coupling numbers $N = 1$, $N = 10$, $N = 100$ and $N = 1000$. We observe a sharp decrease on all bond ratio cases during the intensive sand production. As production becomes in transient regime, the bond ratios increase gradually. These results demonstrate that the bond ratio of the $N = 100$ coupling number is more accurate compared to others and behave in similar pattern with $N = 1$ case.

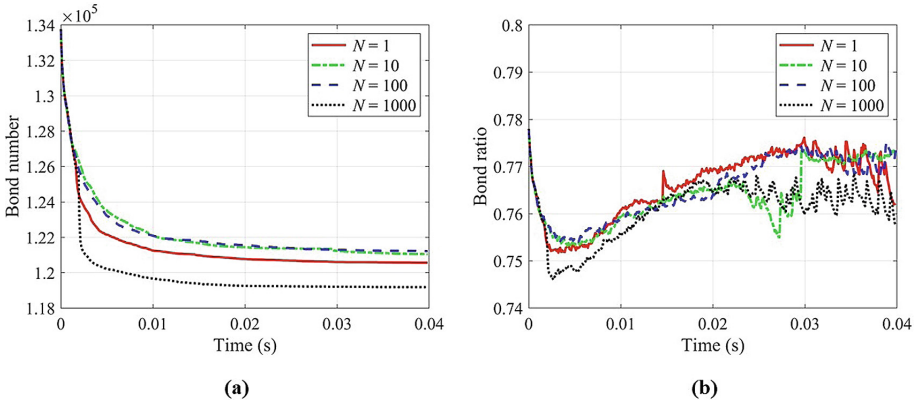

Fig. 5. (a) Bond number and (b) bond ratio of the particles at $N = 1$, 10, 100 and 1000.

We evaluate the CPU time, speedup and root mean squared relative error (RMSRE) to compare the sand production modelling results at different coupling numbers (see Table 3). To examine the accuracy of the simulation results, the RMSRE is given as follows:

$$RMSRE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left|\frac{M^i_{d,N=1} - M^i_{d,N_{coupling}}}{M^i_{d,N=1}}\right|^2} \times 100 \tag{15}$$

where $M^i_{d,N=1}$ is the i-th dimensionless cumulative sand production at $N = 1$ and $M^i_{d,N_{coupling}}$ is the i-th dimensionless cumulative sand production at other coupling numbers.

According to Table 3, the reference coupling number $N = 1$ demonstrates the longest CPU time of 6665 min. The coupling numbers $N = 100$ and $N = 1000$ significantly accelerate the simulation by 8.8 and 9.52 times compared to $N = 10$, which exhibits a speedup of 5.98. These results show that the CPU time of the modeling process is greatly reduced when the coupling number is increased to $N = 1000$. However, this enhancement in efficiency came at the expense of lower

accuracy, as specified by an elevated root mean square relative error (RMSRE) of 5.19% in the total sand production at t = 0.04 s. On the other hand, simulations with coupling numbers $N = 10$ and $N = 100$ provide more acceptable RMSRE values of 1.42% and 1.67% at t = 0.04 s, respectively. Throughout the entire simulation, the coupling numbers $N = 100$ and $N = 1000$ with RMSREs of 4.9% are more accurate than $N = 10$ (RMSRE = 6.05%). In terms of bonding behavior, the $N = 10$ and $N = 100$ coupling numbers demonstrate reasonable results with RMSRE values of 0.68% and 0.65% in bond number, 0.69% and 0.39% in bond ratio, respectively. In contrast, the $N = 1000$ is less accurate with RMSRE of 1.27% in bond number and 0.8% in bond ratio. These findings suggest that a considerable increase in coupling number can improve the computational efficiency, but can also reduce the accuracy of the model.

Table 3. CPU time, speedup and root mean squared relative error (RMSRE) of the sand production simulations at $N = 1$, 10, 100 and 1000 coupling numbers.

Coupling number	CPU time, min	Speedup	RMSRE, %			
			Sand production	Sand production (at t = 0.04 s)	Bond number	Bond ratio
1	6665	1	0	0	0	0
10	1113	5.98	6.05	1.42	0.68	0.69
100	757	8.8	4.9	1.67	0.65	0.39
1000	700	9.52	4.9	5.19	1.27	0.8

4 Conclusion

The main objective of this study is to explore the optimal coupling number of CFD-DEM modeling to ensure physically stable, accurate and efficient results. Specifically, we use the modified JKR contact model to investigate sand production phenomenon in unconsolidated reservoirs, with the particle size distribution and material characteristics being associated with the Kazakhstan reservoir sample. The following coupling numbers $N = 10$, $N = 100$ and $N = 1000$ are taken into account to choose the suitable coupling number for the CFD-DEM simulations. The results are compared with those of $N = 1$, in which the DEM and CFD time-step values are identical. Initially, we provide the snapshots of the flow streamlines, fluid and particle velocities to demonstrate the transient behavior of the sand production. Then, the CPU time, speedup and root mean squared relative error of the sand production results at different coupling numbers are compared. In all cases, the CPU time is significantly reduced compared to $N = 1$. Particularly, the fastest calculations are observed at $N = 100$ and $N = 1000$, in which the speedup is 8.8 and 9.52, respectively. Most of the results show that N=10 and $N = 100$ coupling numbers demonstrate more accurate results compared to the $N = 1000$. Especially, this tendency can be seen from the final sand

production and bonding behavior results. Based on these findings, we consider that the $N = 10$ and $N = 100$ are optimal coupling numbers for the sand production modeling to ensure physically relevant simulations with high accuracy and sufficient acceleration.

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Gender Equity/Equality in Transport and Mobility (DELIA 2023)

Urban and Social Policies: Gender Gap for the Borderless Cities

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Abstract. The variables that insist on the gender gap in transport affect several topics. From being a corporate user or employee, to customs and habits in terms of travel, to sensitivity towards sustainable urban models and proximity mechanisms, in line with the urban transition processes in order with the 15-min city. Analyses of the use of the travel system show that individual choices, also influenced by social inclusion, are decisive. The European Green Deal would represent an opportunity for strategic repositioning in the transport sector towards minimising the gender gap. In Europe in terms of employment, the transport sector is typically attractive for men and less so for women. How are cities re-organising the supply of services, urban amenities and public transport according to changing demand? Is it sufficient to carry out the planning of interventions and resources, the operation of projects, the systematic verification of results in terms of effectiveness and quality of performance, or is a gender impact assessment also necessary? The essay will address the issues related to the new social dimension, beyond gender limits, hypothesising ways and strategies for the functioning of the city without borders, in the era of the multicultural and fuzzy society.

Keywords: Gender gap · Regeneration · Inclusion · Urban planning · Urban transport · Sustainable mobility

1 Introduction

The following dissertation deals with the theme of the gender gap in the context of urban planning and urban transport. From a first analysis of the literature on the concept of the gender gap in urban transport, also in consideration of the recent pandemic phase, the dissertation will answer the research question on how urban regeneration can contribute to bridging the gap. The data of the European indices demonstrating the gender gap at EU level, followed by a dissertation on some case studies referring to projects aimed at bridging the gap, demonstrate what good practices are and what is being done to solve the problem. Then the conclusions that define the guidelines deduced from the study follow [1].

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2 What's Gender Gap in Urban Transportation?

2.1 Concept of Gender Gap in Mobility and Transport Services

In recent years, a number of cities around the world, although still in a tentative stage, are implementing a number of strategies and actions to plan and implement more sustainable and equitable city models and transport networks for all [2–4].

However, the number of women in leadership positions is still minimal in various sectors such as transport and logistics, and women are often confronted with various stereotypes.

The gender gap is highlighted by the variation of the different roles of women in the transport sector, i.e. as a manager but also as a driver or as a simple passenger [5].

Several research studies have pointed out that men's daily journeys are direct journeys, often by a single means of transport (home-work, home-visit), whereas women's journeys are related to multiple modes of transport. This is connected to the fact that it is almost always women who drive their children to school or to various activities, as well as the elderly in the family (mostly business trips) [6, 7].

Furthermore, not only do women and men use means of transport differently, but the factors causing this, such as different social, economic and physical aspects, are also different. Studies worldwide have shown that women are more likely to walk and use public transport as a means of transport. As women's travel patterns are more complex than those of men, these differences show the negative consequences when transport planning focuses primarily on commuting [4, 8].

During the recent pandemic phase, women were the ones who felt most fearful about commuting and reduced their mobility by public transport such as buses, trams and trains [9, 10].

Moreover, recent modal forms such as the use of electric scooters for first- and last-mile journeys are characterised in several cities by a higher percentage of male users, not only because of safety or physical problems in using scooters, but also because women often place great importance on physical appearance and clothing for going to work, and this is often in contrast to the use of e-scooters [11, 12].

A number of researches have pointed out that shared means of transport are more suited to men's physicality just think of tall e-bikes or heavy electric scooters. Vehicles that in any case, unlike men, women would feel safer using in dedicated lanes, away from cars [13].

Public transport, on the other hand, does not seem to be designed for people carrying pushchairs, children, shopping and prams (an even more serious issue for disabled citizens). And there is, finally, the question of safety. Very often women are forced to change lines or skip a stop because they are considered unsafe. All it would take is careful video surveillance, more lighting at the platforms [14].

Several European and non-European cities highlight a number of strategies developed to counter this gender gap.

Barcelona has attempted to prioritise people-centred design and gender inclusion in mobility design by carrying out several actions for the decarbonisation of transport and the transformation of public space, as well as gender urbanism [15, 16].

The city of Buenos Aires is reclaiming street space and the government is attempting to implement strategies to close the cycling gender gap [17].

These actions include, for example, incentives to increase bicycle use, walkability projects and the transition to clean energy. These actions respond to the objective of generating a transformation of citizens' mobility that improves their quality of life and is consistent with the goals set in terms of resilience, inclusiveness and carbon neutrality.

In European cities known for their cycle paths, such as Amsterdam and Paris, the gender gap is in parity. Since the majority of public transport users in many European contexts are not women, there is a need for women in executive level roles to shape a service that affects them more often than their male counterparts [18, 19].

Transport systems can only become truly inclusive and gender-responsive if women's voices, perspectives and experiences are reflected at all levels of the sector. As more women enter the transport sector and assume leadership positions, design and planning for women is gaining importance and it is hoped that we will quickly see the redesign of our transport networks to make them more liveable and human-centred.

2.2 How Much the Reorganization of Transport Can Make the City Inclusive, Case Studies

In order to overcome "marginalization" and "inequality", mobility services (and consequently infrastructures) must improve the social conditions of the citizen. However, many do not oppose social, economic and political life and therefore ensure a more accessible and inclusive life. This happens because barriers often cause a lack of transport networks that are difficult to implement on a municipal or international scale. In the transport sector, planning and design activities to promote accessible mobility for all include the full and active participation of those who live and inhabit cities. Researcher Malvika Dixit's case study at Delft University of Technology led to the combination of smart card data on the public transport network and income data on a smaller scale, the neighborhood. The result of the research was that residents of low density open areas have to travel cumbersome itineraries with relative higher costs to face for tickets. This has led to an understanding of a profound link between income and the complexity of the journeys, in neighborhoods with higher income it is possible to guarantee direct journeys, which leads to lower distances, and therefore costs [20] (Figs. 1 and 2).

Everything translates thus fueling an inequality of a society already divided from a social point of view. What to do for a more socially inclusive mobility? The Boston Consulting Group and the University of St. Gallen in Switzerland analyzed three different cities that share traffic congestion and the presence of underserved, therefore isolated, neighborhoods, such as Berlin, Chicago and Beijing [21] (Fig. 3).

In planning and designing the transport network in these cities, the systems have been adapted to people with disabilities and those coming from disadvantaged socio-economic backgrounds, such as for example the use of shuttles that bring them closer to the stations or car sharing at affordable prices. Furthermore, both supply and demand must be taken into account, for example it was realized in Chicago that increasing the frequency of night transport does not necessarily lead to a greater flow of passengers. These are measures that must go hand in hand with the real understanding of the demand and user preferences, for example if you want to increase the use of the subway by adding



Fig. 1. Research Boston Consulting Group and University of St. Gallen - self-driving vehicles (AV) Source: https://slowrevolutionitalia.wordpress.com/2021/01/04/veicoli-autonomi-contro-il-traffico/



Fig. 2. Chicago. – aerial gondolas. Source: https://design.fanpage.it/chicago-skyline-i-futuri-mezzi-di-trasporto-in-citta/;



Fig. 3. Bejing. - transit elevated bus. Source: https://ilgiornaledellebellenotizie.com/2016.

rides or carriages to trains it will not help, but you could consider a first class service for this band of users thus allowing to improve travel conditions. An important role is also played by innovative and modal transport systems that go beyond mass transport, among these we find car-sharing applications, micro-mobility offers - bikes, scooters, scooters -, shuttles on request. This type of system can also help in finding innovative solutions to combat climate change. Another aspect not to be underestimated is the involvement of local communities in the decision-making process through data collection ensuring an accurate analysis of the choice and the possible problems and obstacles that can be solved [22].

Basically, most of the transport systems have the same appearance and function as in the 1950s, what changes today is society with the sole objective of promoting socio-economic growth and social equity. This can ensure jobs, access to various social and cultural services and therefore progress up the social ladder as mobility should not be seen as a tool that simply 'moves' people from one place to another. Today, however, these social changes, with respect to mobility that has remained unchanged, have led to a gap between the needs of citizens and the ways of moving guaranteed by cities. What limits this development of mobility is dictated by the fact that the system at a physical and socio-economic level does not benefit from some solutions that technology itself offers us - such as on-demand shuttles or apps for sharing means of transport.

3 What's Gender Gap in City Planning?

3.1 How Much the Reorganization of Transport Can Make the City Inclusive, Case Studies

The sudden development of urbanization is bringing strong pressure on environmental life and above all on social and economic results that take into account factors such as accessibility, inclusion, quality of life and resilience. We need to sensitize the various countries to work on initiatives and resources to fight social inequalities, forms of poverty and climate change all under an inclusive key. It is necessary to guarantee mobility and transport systems that are safe - also from a road point of view -, accessible by all and sustainable for the different needs of users - women, children, the elderly, people with disabilities [23] (Fig. 4).



Fig. 4. Global Gap Report 2022: selected examples, cities on all over the world. Source: https://www.thegoodintown.it/la-mobilita-come-strumento-di-inclusione-sociale/

This must not involve "special" planning and design for the most vulnerable users, but guarantee universal access to green and public environments by guaranteeing their inclusive factors. This would involve not only an environmental and sustainable benefit but also an optimization of social and psychological costs. To obtain these results, it is necessary to launch large initiatives with large investments of resources, planning activities and monitoring systems. It is possible to observe that if on the one hand temperatures are constantly growing, on the other hand society is constantly evolving and growing in terms of habits and environment. Resilience is today a necessary component for sustainable and accessible development, acting first of all on the organizational and management models of urban systems. Accessibility policies must provide for correct information on the use and destination of services dedicated to the most vulnerable people - women, children, the elderly, people with disabilities -, as well as the promotion of initiatives dedicated to the use of sites of tourist interest and cultural by the same without, however, alluding to a "special" type of planning and programming. Public

administrations are not the only ones to play an important role, but so are the city users who populate and experience these spaces firsthand. The problem with our country is that it is characterized by unique cities rich in history and art, and often these do not allow them to be enjoyed by everyone due to their artistic and touristic heritage. However, all this is not impossible, the enhancement of the accessibility of the territories could be ensured through a plan to improve the conditions of mobility - regional, provincial or municipal roads - taking into account the population that inhabits these places. One could start from an adaptation of the flooring, and therefore of the signage and lighting, creation of paths and reduction of environmental pollution in order to improve the conditions for the protection of public safety and exposure to hydrogeological risk [24].

3.2 Gender Impact: Which European and National Guidelines?

A definition of urban planning: "a multidisciplinary approach that defines where to build and why. Urban planning is conceived as a relationship between people and the built environment, so that this environment is made livable and the conditions of the people inside it are perceived as safety and well-being. Urban planning achieves these objectives through the protection and development of the environment, transport, housing, public spaces and urban design" (Fig. 5).

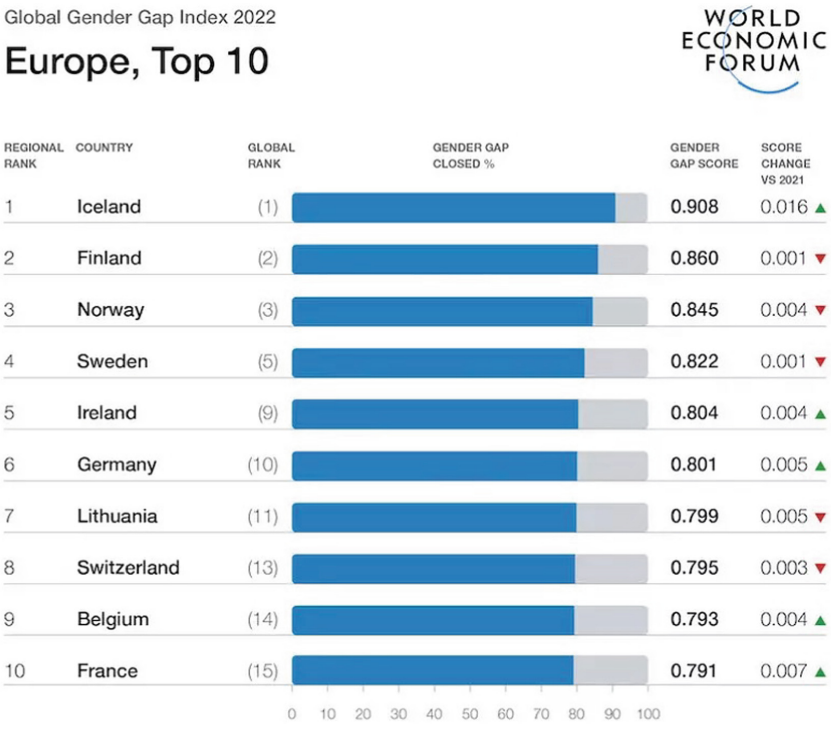

Fig. 5. Global Gap Report 2022: Global Gender Gap Index. https://www.weforum.org/reports/global-gender-gap-report-2022/

Although gender inequality in social, cultural and economic terms has greatly improved towards social equity in recent decades, it is still a current and ever-changing theme [24]. The system of gender difference is in fact determined by cultural constructions dependent on the temporal sphere in which they function. Therefore conditioned by society and by historical moments in which mainly political factors contribute [25].

The Global Gender Gap Report 2022 [4] found that the global gender gap has been closed by 68.1%. Although the figure is defined as slightly improving, it is necessary to consider the generational loss of the two-year period '20–21 (also aggravated by the global pandemic condition) which has clearly increased the trend according to which in 2020 this gap would be filled by 2120, postponing it until 2156.

What are the indicators able to define the aforementioned trend? Mainly these are four macro areas:

1. health;
2. education;
3. economic opportunity;
4. political participation.

In the 146 countries covered by the indicator, the gender gap has narrowed significantly between health and survival and on the level of education by 94.4%; sufficiently regarding the economic opportunities of 60.3%; however only 22% in the area of political participation.

The international comparison sees North America leading all regions, having filled 76.9% of the gender gap, followed by Europe, which filled 76.6% of its gap. Asia (Central and Eastern, because Southern Asia remains at the bottom of the ranking) is positioned only towards the middle of the ranking, making up 69%. More than four percentage points less for sub-Saharan Africa, the Middle East and North Africa, which closed 63.4% of the gender gap

Europe holds the second place in terms of gender equality - at 76.6%. It is certified that the gap can be filled in 60 years on average.

Gender gaps are influenced by several factors. Cultural revolutions, political debate, economic and technological transformations. In particular, in recent decades, the 2008 crisis has played a fundamental role, limiting the sectors that provide the core of the social infrastructure, influencing the outcomes for families and primary health workers which was then followed by a further aggravation during the pandemic.

Furthermore, the gap is also suffering from geopolitical conflict, in Africa, Asia and Eastern Europe and from climate change.

On the economic issue, the countries that lead the performance in this sub-index are Sweden, Latvia and Iceland, while Italy, together with Bosnia Herzegovina and North Macedonia are at the bottom of the ranking, ending 2022 with a development indicator below the 70% threshold - compared to a ranking governed by countries with an improvement of more than 10 percentage points over Italy.

What steps are being taken in designing future scenarios leading to a zero difference? The European Commission in 2021 presented the "EU Action for Equal Pay", with the intention of tackling the gender pay gap with the aim of "promoting the effective

principle of equal pay by creating new legislation and monitoring its implementation". The measure, with 24 action points, distributed in 8 main strands of action, aims to:

- improve the application of the principle of equal pay;
- combating segregation in professions and sectors;
- break the glass ceiling: tackle vertical segregation;
- face the care penalty;
- make better use of women's skills, efforts and responsibilities;
- discover inequalities and stereotypes;
- warn and inform about the gender pay gap;
- strengthen partnerships to address the gender pay gap.

In December 2022, the Law on Equal Pay [26, 27] was published in No. 285 of the Official Gazette of the Italian Republic, aimed at raising awareness of those who oppose the phenomenon known as the gender gap. The certification of gender equality had already entered into force in January, which attests to the obligation adopted by companies and administrations - with more than 50 employees, those with fewer only on a voluntary basis - to draw up a report on gender inequality every two years.

At it stands, gender impact is believed to be suffering from the climate crisis; women, together with the most vulnerable minorities, are more severely impacted than men. This is due to persistent social, cultural, economic and political inequalities. It is necessary to discuss and deliberate innovative strategies in terms of energy regulation and the fight against climate change in order to support minorities who are victims of gender inequalities.

3.3 Gender Impact: What is the State of Implementation of the Projects and the Results Achieved? A Review

The report "Why the European Green Deal needs ecofeminism - Moving from gender-blind to gender-transformative environmental policies", maps gender gaps and opportunities. And, it also provides recommendations on how to move from gender-blind environmental policies to environmental policies that bridge the gender gap (Fig. 6).

In the context of urban planning, the relationship between cities and vulnerabilities also includes the issue of gender inequality [28, 29]. In terms of perceived security, in fact, the urban morphology is subject to describing areas of "freedom" and not. Certain contexts, in fact, are more subject than others to gender inequalities. Although, as widely stated, the theme of the gender gap is national and European, as well as international, in some areas, due to the social and cultural context, these phenomena tend to be negatively amplified.

The Handbook for Gender-Inclusive Urban Planning Design is a document that identifies six so-called "discriminating" areas for the female gender in the context of perceived safety. Also connected to the issue of the ability to counter and mitigate the effects of climate change.

The role of urban planning as a practice of modeling the environment determines the way communities live in a specific place. Planning is therefore closely connected in the definition of urban processes also in social terms with respect to the inequalities inherent in the population. In this sense, urban planning can act as a programmer of conditions

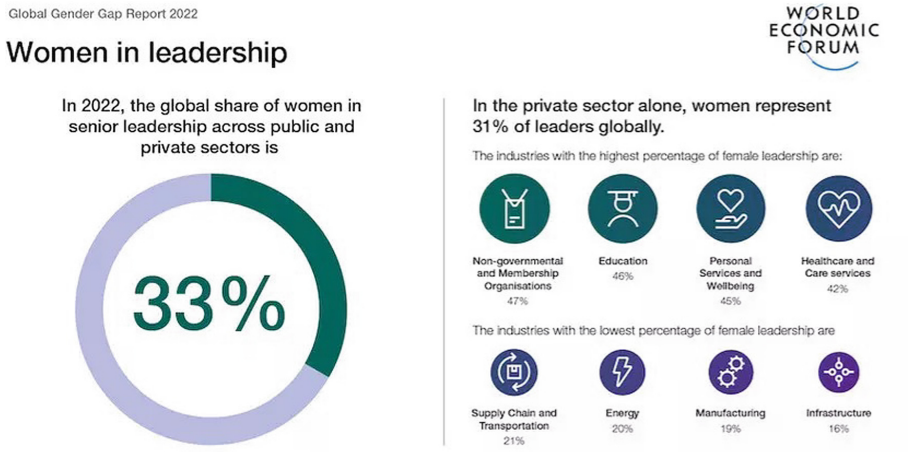

Fig. 6. Global Gap Report 2022: women in leadership. https://www.weforum.org/reports/global-gender-gap-report-2022/

that make the lived environment safe with respect to the gender gap. In other cases, in fact, the urban fabric increases inequalities (Fig. 7).

What is the appropriate way to plan urban transformations taking into account inequalities, towards an objective of social equality within cities?

In fact, the urban planning discipline catalyzes issues such as that of public transport, infrastructural mobility, the urban landscape, public space, basic urban services, energy [30]. Case studies of gender-inclusive projects in cities show how simple measures to improve urban access can significantly increase safety and well-being, as well as liveability. Below is a review of some European projects on the subject [31]. “EUROPA - MIND THE GAP [32]: towards gender equality", quoting the famous phrase from the London subway, is a European project whose promoters are Italy, Belgium, Portugal and Spain. It is proposed to achieve a general macro-objective by addressing gender stereotypes in schools, thus reducing the influence of gender expectations on the choices of girls and boys in matters of education, work, and life choices, and a specific one aimed at strengthening ability of educators and other adults dealing with children to identify and address gender stereotypes in education, including their own unconscious biases. Through certain lines of action, it basically aims to:

– discover and deconstruct gender preconceptions;
– combating gender segregation in study disciplines;
– deal with stereotyped social implications together with students by encouraging them to deconstruct negative gender roles that fuel the gap;
– integrate the gender perspective into guidance practices and psychological counseling to support school structures.

The STEAMiamoci project [33] aims to “promote concrete actions to reduce the gender gap because STEM skills are and will be the skills of the future”.

Indeed, the data on university enrollments show that women represent the majority of enrolled students (55%), however in STEM degree courses the data records only 37%

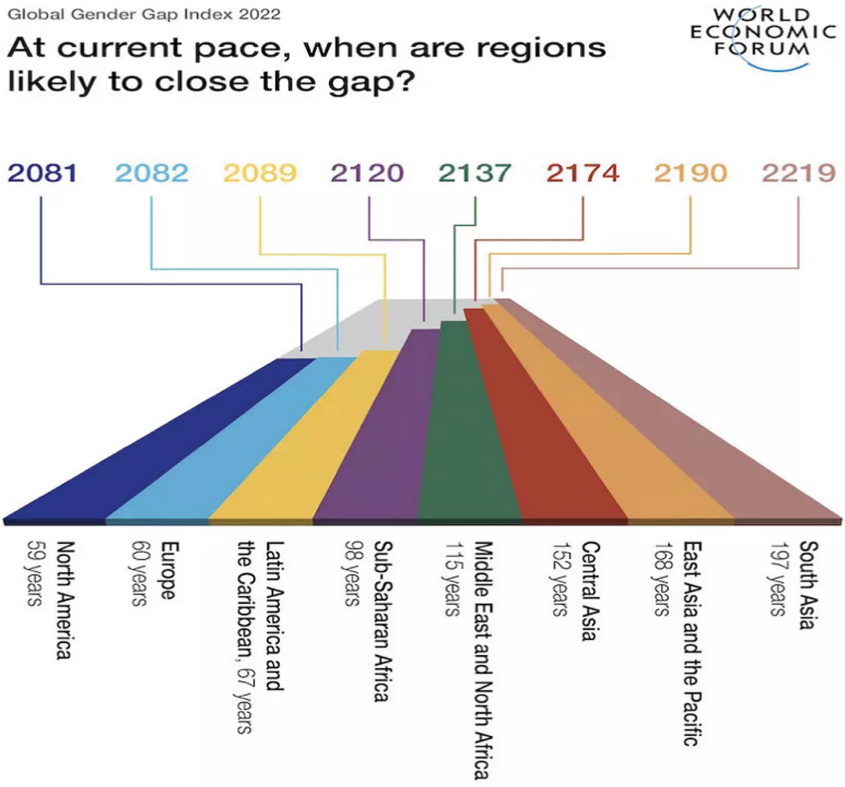

Fig. 7. Global Gap Report 2022: the regions and the gap. https://www.weforum.org/reports/global-gender-gap-report-2022/

of female presences among scholars. In fact, the research shows, as the most striking fact, that 82% of those enrolled in the humanities are female, while only 20% of enrolled women attend engineering courses.

Among the objectives of the project are:

- organize the current situation in order to provide elements to guide university policies;
- provide tools for communication and media dissemination activities;
- organize orientation days with managers specifically trained to state the benefits of attending STEM university courses for future access to the world of work;
- promote the visibility and sharing of best practices;
- increase school-business-institution activities and collaboration on the subject.

The GE&PA - Gender equality and public administration [34] project offers training courses for gender equality in the PAs - co-financed by the Emilia Romagna Region - with the aim of making communities capable of assuming such skills so that public policies are directed towards European and national gender equality goal.

A community is able to bridge gender inequalities by pursuing urban objectives of accessibility, networks, security, climate resilience.

4 Conclusions

Case studies analized on gender-inclusive projects in cities show how simple measures to improve urban access can increase safety and well-being, as well as liveability. The principle of equal opportunities between women and men is found precisely within the structural policies.

of the European Union and has an increasingly significant importance, as known, starting from the Platform action adopted at the Fourth World Conference on Women held in Beijing in 1995, to then continue with the Treaty of Amsterdam, in which the member countries have provided for formalize the commitment and attention towards equality policies and mainstreaming at European level, in particularly starting from the regulations of the structural funds for 2000–2006 [35].

Precisely the regulations represent a culminating point of the process started at Community level, identifying in the indication of equal opportunities one of the priorities to which all member countries must.

strive in the implementation of programming, and a concrete way to impress greater strength to take gender issues into account.

The regulations establish that programming incorporated into the set of policies and actions identifies the application of the principle of mainstreaming. This means always having as a reference, in all the fora of definition of policies and typologies of intervention, the attention to the possible different effects on the respective conditions of women and men, i.e. the assumption of a gender perspective which leads to systematic questioning of such actions and policies in their significant differentials for gender [36].

Contribution Authors Corresponding authors: although the research is the result of the work carried out jointly by all the authors, which Celestina Fazia is the supervisor, the drafting of the essay is to be attributed differently to each of them:

§ abstract and introduction by Celestina Fazia; § 1.1 by Tiziana Campisi; § 1.2 by Giulia Fernanda Grazia Catania; § 2.1 by Celestina Fazia and Giulia Fernanda Grazia Catania; § 2.2 by Dora Bellamacina; § 2.3 by Dora Bellamacina; § Conclusions by Celestina Fazia and Tiziana Campisi.

Essay review: Tiziana Campisi.

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A Two-Steps Analysis of the Accessibility of the Local Public Transport Service by University Students Residing in Enna

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Abstract. The attention to a sustainable environment and mobility has increased significantly in the last two decades, directly linked to human and economic activities. Such a sustainable agenda can only be implemented through a strong interaction between the economic actors involved, aware of the transport choices and their consequences. Similarly, a university campus in an urban context requires in-depth studies on the balance between supply and demand for transport dedicated to the university population. These users have different daily or weekly travel times from those of the resident population and travel frequencies that are not always constant. The result is a highly segmented demand for local (LPT) and regional (RPT) transport, which needs to be investigated to improve services and infrastructures and to ensure that all university students can choose sustainable forms of transport and give up using private motorized transport.

The present research focuses on assessing the characterization of the resident and university population with domicile in Enna Alta and analysing the public transport offer that allows the connection between Enna Alta and Enna Bassa. Specifically, this study considered a double-step investigation of accessibility in topological and spatial terms by implementing QGIS and isochrone calculation. The research is novel as it highlights the implementation of a system that allows easy tracking of accessibility isochrones through the use of open-source GIS software, which in addition to being free, is highly adaptable to different technical requirements. Findings suggest that only the northeastern part of the city has good accessibility. Similarly, the connection between upper and lower Enna through the LPT service provides valuable indications to local authorities. These authorities could collaborate with the University governing bodies to implement policies of green commuting, trying to enhance public transport and reduce the number of private vehicles by promoting new forms of shared mobility, such as carpooling or car sharing. The results lay the foundations for further comparative studies and provide a starting point for local transport service managers to optimize the sustainable transport offer and therefore allow a reduction in the use of private transport.

Keywords: Sustainable mobility · Local public transport · University city campus · University student accessibility

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1 Introduction

Rapid urbanisation has led to a massive transformation of urban space in several European countries in both spatial and social terms [1]. It is closely related to the travel frequencies and modal choices of users living in or travelling to and from cities. In recent years, we are witnessing the creation of several campus cities in which the percentage of students is substantial concerning the local population [2–4].

Several studies in the literature have drawn attention to the different modal choices made by university students, including more recent choices such as shared mobility. It is crucial to analyse public transport to optimise the movement of several individuals to similar destinations with the same purpose of home-school or home-work. In some contexts, such as China, higher education has grown much faster than in the past, with an explosive increase in the university population. Unlike Western universities, most Chinese university students have to reside on gated campuses. Their accessibility to public transport and the resulting spatial and social implications have been neglected in the literature.

A study conducted by [5] analysed the concept of spatial accessibility through four methods: proximity-based, gravity-based, population-weighted average, and competition-based, using population data at the residential building level. All results confirmed the presence of spatial and social inequalities in public transport accessibility for university campuses and student populations. The study also found that these inequalities are not directly due to the provision of public transport services but to the closure of gated campuses to external public transport.

A study by [6] determined the factors influencing the quality of public transport service and the student demand for public transport. The study found that convenience is the most important factor for bus service quality, followed by service planning and the bus network. The most important factors influencing the intention to increase bus use are attitude, personal norms and the lack of a private vehicle. All three factors positively affected the intention to increase the use of the au-bus. One factor that had a negative impact was the perceived behavioural control in increasing bus use. Socio-economic factors such as hometown, gender and academic year did not directly depend on increasing bus usage, but had an indirect effect through vehicle ownership.

Several European and non-European states, to be able to implement a series of sustainable policies and strategies under the United Nations' Agenda 2030 and the European Green Deal, have highlighted the need to implement a series of urgent solutions to improve people's quality of life, encouraging, especially in systematic mobility, the use of alternative and more environmentally friendly modes of transport than private vehicles.

Commuting students to and from university campuses has a substantial social, environmental and transport impact. A study in Portugal by [7] analysed the modes of transport used by a group of students in their commute, the potential for switching to more sustainable modes and the respective CO2 re-splitting considering two scenarios: an optimistic one and a more likely one. The results described in this study can help university campus managers and planners to adopt planning policies to make mobility more sustainable.

This study focused on a double level of analysis of topological and spatial types. It is connected to implementing open-source geographic information medium QGIS and considering the calculation of isochrones related to distances between residential areas and local bus stops. This double level of investigation made it possible to emphasise that there is currently no homogeneous spread of the examined context of accessibility to local public transport by university students living in the historic centre.

These results highlight the need to implement more sustainable mobility strategies with a greater spread of transport services to counteract the use of private cars. Specifically, Sect. 2 analysed the growing development of city campuses worldwide and highlighted the main factors influencing university students' use of specific modes of transport. Section 3 focused on the Italian context, and recent studies analysed the demand and supply of mobility for university students prevailing in some regions. In Sect. 4, the double level of analysis was detailed with the methodology definition and implementation of QGIS and isochrones calculation. Finally, in Sect. 5, some considerations and conclusions to the research are presented.

2 Literature Review

The Italian system is composed of a total of 97 university institutions, of which 67 are State Universities. In addition, 19 legally recognised and 11 non-state universities are also legally recognised. Different types of cities (size, location, number of inhabitants) are today home to one or more university campuses located in some cases in the context of the historic centre or, in most cases, in expansion areas [8].

The ability to successfully achieve positive and negative effects from the urban location of these large traffic-generating institutions is crucial for the development of university campuses and the city's liveability. A study conducted at the University of Trieste has shown how transport mode choices are made by teaching and administrative staff and students at the various locations where academic activities occur and how they would be influenced by eight different transport management policies [9].

Numerous universities worldwide and in Italy have adopted initiatives to reduce the environmental impact of the mobility of the entire academic community. A study conducted by [10] in Thessaloniki shows how the walking distance accepted by students to reach the public transport stop can increase if a higher frequency of the service is guaranteed. In [11], it is highlighted how, starting from the study carried out in Moscow, Idaho, low-cost parking allows one to use the car for shorter distances. A study conducted by [12] in the Grenoble Metropolitan region of France classified the studied area according to the various level of active and public transport accessible zone; among the factors influencing accessibility are intersection density and land use. Researchers conducted a study on student mobility at the University of Foggia, in Apulia, to survey and assess the mobility routines of community members (students, academic and administrative staff). Through the administration of a questionnaire, several useful contingency tables were defined for the statistical description of the main means of transport used by the members of the university community and their emissions [13].

Several research studies in recent years have underlined the factors that most influence the modal choices of this target group. A study by [14] examined the travel habits

of students and staff of a medium-sized public university campus in a peripheral area of the city of Varese (northwest of Italy), far from the suburban railway and bus stations and with many green spaces. The main results highlight the crucial role of the proximity of public transport (bus and train stations) in both short- and long-distance travel. Other factors influencing the choice of transport mode include the age of commuters and, to some extent, gender, frequency and length of trips. In contrast to the results of the empirical literature on urban colleges, we found a positive correlation between distance and train use.

Many studies, both in Italy and abroad, have focused on the assessment of travel time to estimate accessibility to university campuses through both local public transport and shared mobility systems [15, 16]. Some studies have analysed both intra- and extra-urban university travel by considering both trajectories using special GPS devices [17] and, more important, student mobility trajectories between macro-areas and disciplinary areas and emphasising the influence of such travel by considering previous travel and mobility choices related to education at higher education institutions [18, 19].

A few studies have focused on analysing the accessibility of city campuses considering the implementation of QGIS and the calculation of isochrones. This type of investigation requires data related to the dislocation of infrastructures and the analysis of the housing locations of the target users to be analysed as well as correct and up-to-date information on public transport services in the examined area.

Starting from this, the present work set itself the objective of understanding the possible propensity of university students living in the historical centre area in Enna in Sicily to use local public transport to reach the university campus. Therefore, as a first step, the research investigated the distribution of inhabitants and university students in upper Enna in Sicily by reconstructing the current layout based on territorial information support. In the meantime, the present infrastructures were analysed with particular reference to the distribution of urban bus stops and the local public transport offer was analysed, which allows the connection of the area of Enna Alta (on the top of the plateau) with the context of the university campus located at the base of the plateau. Finally, the distance of the main areas inhabited by students with the urban bus stops was estimated through the estimation of isochrones from which it is possible to understand how distance can influence the modal choice of public transport.

Therefore, paragraph 2 defines the methodology conducted while paragraphs 3 and 4 analyse the case study results and highlight in the concluding part possible directions for strategies to improve public transport services and better urban and mobility planning that can take into account commuter population groups such as university students.

3 Methodology

The analysis developed in this article aims to propose a methodology for evaluating the collective public transport service in an urban reality in which the distribution of student residences and the public transport offer is known. The proposed methodology is divided into two steps:

– analysis of the territorial distribution of students;

– analysis of the accessibility of the LPT supply system.

To analyse the territorial distribution, a study is carried out related to the possibility of clusters of areas, defined according to the demand criterion to be analysed. To do this, the Moran scatter plot is used. The performance of a variable in the x-axis is represented, and that of its spatial lag in the y-axis; in this way, the presence of spatial auto-correlation for the variable can be identified.

From the Moran scatter plot, it is possible to determine Moran's MC coefficient, a spatial autocorrelation coefficient that makes it possible to verify the existing correlation between a variable and its spatial lag [20, 21]. It is defined as:

$$MC = \frac{N}{W} \frac{\sum_{i=1}^{N} \sum_{j=1}^{N} wij(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{N} (x_i - \overline{x})^2} \quad (1)$$

where:

N is the number of spatial units, with indices i and h;
x is the variable considered;
x- is the mean of the variable x;
wij are the elements of a spatial matrix, with wii=0;
W is the sum of all wij.

For the analysis of LPT accessibility, different approaches are proposed in the literature [22–24]. Attention has been paid to accessibility by persons with disabilities [25, 26]. Among the mathematical tools in the literature for the analysis of LPT accessibility, one interesting tool is that of isochrones [27]. Isochrones are used both for the analysis of the existing network [28] and for the evaluation of improvement interventions [29].

The paper intends to propose a methodology that considers pedestrian isochrones to evaluate the accessibility of the LPT system, discretizing the service by lines and user categories. It is proposed to evaluate the pedestrian isochrones related to each stop of each line, measuring the rate of a population segment included. The objective is to have a tool to compare the lines with each other according to the population groups most affected, relating them to the spatial distribution analysis carried out previously. Consider the study area characterised by a number $n = 1,2,\ldots, N$ of zones, each characterised by an area An and a population P_n. Consider a public transport system characterised by many lines $l = 1,2,\ldots, L$. We define the area generated by the union of the areas delimited by the isochrones obtained from the LPT stops belonging to line l. For each area il relative to line l, it is possible to evaluate the area obtained from the intersection with the generic A_n; the intersection area is defined as $A_{n,l}$. For each area n we consider the population P_n uniformly distributed within the area. The estimation defined $P_{n,l}$ as the share of the population P_n contained within the area $A_{n,l}$ evaluated as:

$$P_{n,l} = \frac{A_{n,l}}{A_n} P_n \quad (2)$$

The total population P_l within area il is obtained as:

$$P_l = \sum_{n=1}^{N} P_{n,l} \ \forall l \quad (3)$$

4 Case Study and Results

4.1 The Territorial System

The case study focuses on the city of Enna, an Italian municipality and provincial capital, located in the central part of Sicily. About 25,000 inhabitants inhabit the city, and there are also about 8,000 university students. The built-up area is divided into two geographically clearly separated areas: the historic urban centre (Enna Alta), with a resident population of about 15,000 inhabitants (Source: ISTAT), located on a plateau and the expansion area Enna Bassa, where some of the most recent structures are located, in particular the University.

The characteristic of the case study makes it particularly interesting: the presence of the University and numerous educational institutions located in lower Enna, against a majority of the population living in upper Enna, makes the optimisation of LPT vital. In the case study, the LPT lines connecting Enna Alta with the outside are analysed; their accessibility within the Enna Alta Study Area is evaluated. The aim is to assess whether the lines for home-study trips are accessible.

4.2 Spatial Distribution

The province of Enna is located in the heart of Sicily and its capital has been identified as the island's geographical centre; despite not having access to the sea, it has a rich natural heritage. It extends over 2,562 sq km (10% of the regional area), the fifth Sicilian province in territorial extension and the ninth in inhabitants.

The province of Enna, physically located in the island's centre, represents an important road link between three large areas of Sicily: the eastern, central and north-western parts. It is crossed by the motorway network, which directly connects two large municipalities in the region, Palermo to Catania and which at the same time facilitates travel between several municipalities in the province through the five junctions it has. Various state roads are grafted into this network which connect the larger municipalities especially towards the capital municipality and a capillary network of provincial roads which, extending for over 1,500 km, guarantee the local road system.

Slopes characterize the geographical and morphological conformation of the study area; furthermore, a central area characterized by good pedestrian access, with sidewalks in good condition, corresponds to a less well-stocked peripheral area. Overall, the most pedestrianized areas are those crossed by the main road axes, Viale Armando Diaz, oriented in a North-South direction in the western part of the study area, and Via Roma, oriented in a West-East direction, in the eastern part of the area.

The city of Enna has been the seat of the University of Enna Kore for about 18 years and for a few years of a second university called the "Dunarea de Jos" University of Galati. In recent years, this has led to around 8,000 students, around 60% with rent or a home in the context examined. The data used are obtained from ISTAT annals [30], and the implementation was carried out on QGis concerning the study of accessibility [31]. The accessibility range is 5 min, considering an average speed of 1 m/s. The spatial autocorrelation analysis, defined in Chapter 3, was performed on R [32]. With a scale of values from white (zero population) to dark red (460–659 inhabitants), as shown

in Fig. 1, the study area was analysed considering adopting a discretisation approach (ISTAT 2023).

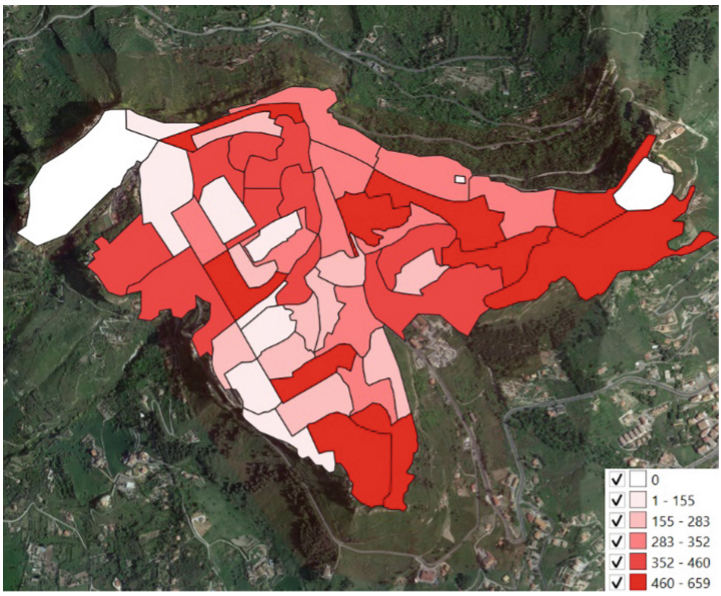

Fig. 1. Case study area and relative residential inhabitant distribution (Source: Authors elaboration by QGis software; background source: Google)

The distribution of students as a percentage of the total population is shown in Fig. 2.with colours from lilac (zero students) to dark purple (more than 12 students).

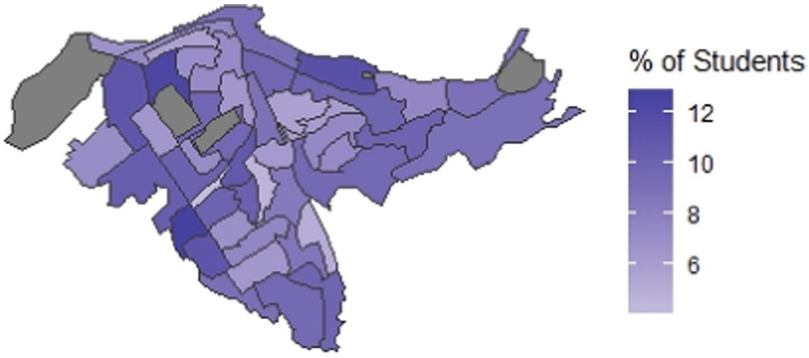

Fig. 2. % of students over total population (Authors' elaboration by R software)

The autocorrelation analysis is carried out by performing the Moran scatter plot analysis and the Moran coefficient study. The results are shown in Fig. 3.

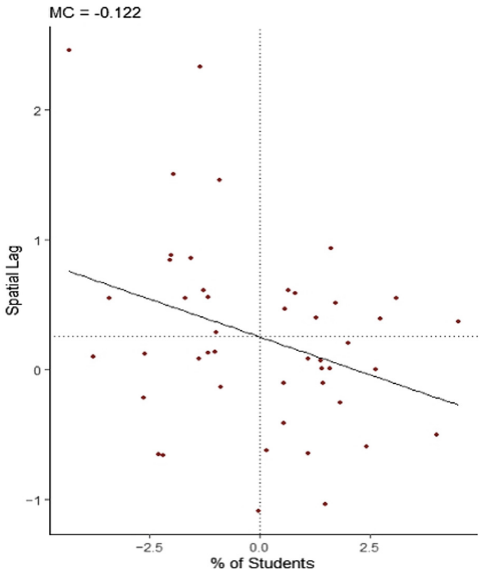

Fig. 3. Moran scatter plot (Authors elaboration by R software)

The analysis shows an absence of patterns in the distribution of students. The calculation of the Moran coefficient returns a value of MC $= -0.122$, which indicates a slight negative spatial autocorrelation.

This makes it possible to state that there are no clusters of areas particularly populated by students, which maintain a homogeneous distribution in the area; rather, it occurs that each area with higher than average percentages of students is surrounded by areas in which the value is the same or slightly lower; similarly, areas with low percentages of students border on areas in which the value is higher than average or about the same.

This does not allow clusters of zones to be identified, and for separating the area into parts more or less populated by students, it is sufficient to characterise them by observing only the values for each zone. From the distribution analysis, the areas characterised by higher student density are mainly located in the western part of the study area, without showing a clear spatial pattern.

4.3 Accessibility of Public Transportation System

The local public transport service is divided into five lines. Of these five, the first is entirely within the study area. Lines 2, 3, 4 and 5 represent the focus of the research under examination, since they concern the connections of the urban area of Enna Alta with the outside world. In particular:

- Line 2 denominated Valverde – Ospedale that, connects the eastern part of the city with Enna bass and in particular with the Hospital
- Line 3 denominated Spirito Santo - Ferrante connects the south-west part of the city with the area where some university faculties are located

– Line 4 denominated Parcheggio Pisciotto - Piazza Garibaldi, which connects a car park near the historic centre with the centre itself
– Line 5 called Terminal Enna Alta - Pergusa connects the terminal bus located in Enna Alta with the village of Pergusa.

Of these lines, the third line connects the centre with the Pisciotto car park. It therefore does not reach the university area; however, the study is carried out, as this line can be used to access the car and therefore has a multimodal function. A substantial part of the stops are located near the road axes referred to in paragraph 4.2; the good pedestrianization of these areas makes it easier to reach the bus stops; sidewalks less cover peripheral areas. Overall, therefore, we have $L = 4$ lines and $N = 51$ zones. The variable P_n used to measure demand is the student population residing within zone n. The results expressed in terms of student population per line are shown in Table 1

Table 1. Bus lane and % of polution P_l distribution

ID bus line	From - To	P_l
1-route 2	Valverde - Ospedale	40,02%
2-route 3	Spirito Santo - Ferrante	64,01%
3 route 4	Parcheggio Pisciotto - Piazza Garibaldi	37,15%
4 route 5	Enna Alta - Pergusa	31,89%

As can be seen, only Line $l = 2$ covers more than 50% of the student population. This is due, in large part, to the fact that it is the line located in the Central-Western part of the city, the one with the highest average density. Lines $l = 1$ and $l = 3$ share an important part of the route, both being located in the Central-Eastern part of the study area. Line $l = 4$ has the fewest stops within the urban area and covers the smallest part of the population.

Of the identified lines, only line $l = 2$ and partly line $l = 4$ cover the western area, which is the most populated. Only line $l = 2$ covers the South-West part of the study area. Figure 4 shows the example for evaluating the isochronous $l = 4$, the Enna Alta-Pergusa line. The main local public transport stops are shown in red, served by bus routes 5.

The LPT connection system is finally evaluated by considering the union of the 4 isochrones considered. The result is shown in Fig. 5.

As can be seen, only part of the settlement in the central and eastern areas are excluded from the overall isochrony. In terms of student population, the overall PTOT value is PTOT = 84%.

5 Discussion and Conclusion

The dislocation of university campuses generates many commuters who need services, including sleeping and living facilities. Depending on the expansion of the cities, some campuses originated in the historic centers. However, most Italian cities have foreseen

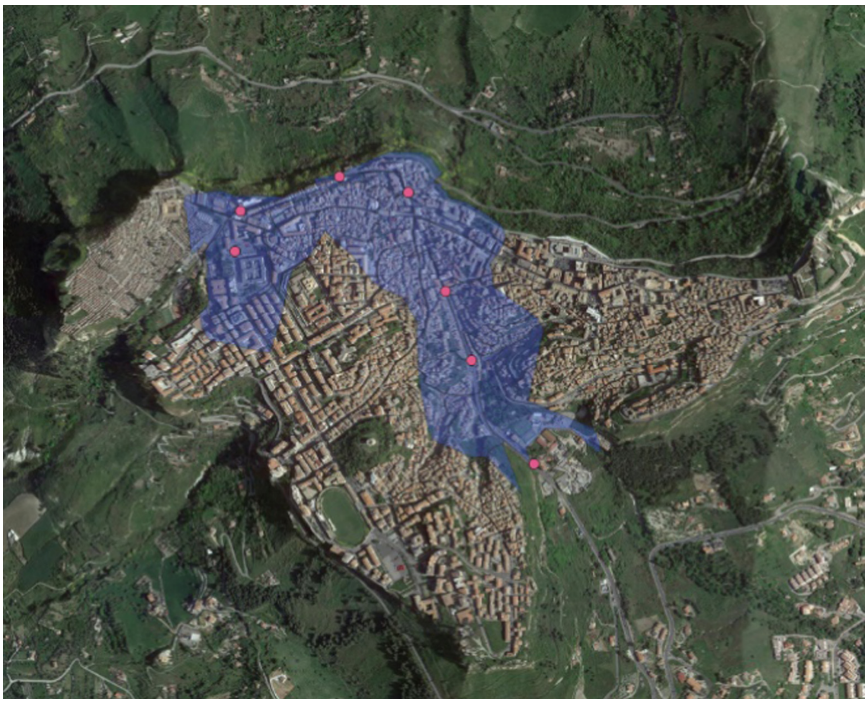

Fig. 4. Isochrone Enna Alta-Pergusa (l = 4) (Source: Authors elaboration by QGis software; background source: Google)

the location of university campuses in peripheral or expansion areas. The development of university cities must be properly planned to ensure that cities with historic centers are easily accessible and inhabited by university students if the campuses are inserted in expansion areas.

The present research work has set itself the objective of analyzing the geographical distribution of the student population in the part of the historic center of the examined area, verifying whether the current LPT system allows good accessibility in terms of territorial coverage for the identified class. Starting from these concepts and considering the dislocation of the census units, the distribution of students was observed in the examined context, which is non-homogeneous.

Considering the case study, it can be observed that the western area has a greater student population than the eastern area of the historical center. Considering the local public transport offer, the distribution of 5 different LPT lines was considered, which allow the connection of the historic center with the other main areas of the city where offices, hospitals and university facilities are located.

The results show an uneven coverage of the areas starting from the study of the isochrones. It should be noted that although lines l = 1,2,4 connect Enna Alta with Enna Bassa, only line l = 1 connects Enna Alta – Est with Enna Bassa, covering 40% of the student population. Line l = 2 reaches most of the population (more than 60%) and covers the entire western area. The l = 4 line only covers the central and northwest area,



Fig. 5. Isochrone union 5 min i_{TOT} per le linee l = 1,2,3,4.

for just over 30% of the student population. More than 80% of the student population is located less than 5 min from a local public transport stop which refers to one of the lines connecting with Enna Bassa.

The results obtained from the double level of analysis on a QGIS basis and the calculation of the isochrones allow us to underline that in the examined area there are no districts which, on a large scale, have characteristics of "student districts". Therefore, it is underlined that the area of the historic center remains inhabited by residents.

Furthermore, it should be noted that the Enna Alta area is covered by accessibility in 5 min, with more than 80%. However, this coverage and, therefore, this estimate of accessibility to urban public transport is spread unevenly among the various lines, with some areas covered by several lines and others covered by a single line.

This result should push the transport service manager in synergy with the local administration to have to implement some services to improve and make the modal choice of urban bus transport more usable and, at the same time, have to implement a series of strategies that can encourage the use of this modal choice, for example by applying discounts, preferential fares or by defining lanes dedicated to public transport.

This research work is the first step in evaluating the accessibility of public transport by the university students of the examined area. In order to improve the accessibility of the historic center, a survey is also planned on other target users, such as older adults. An application of a methodology for assessing accessibility to public transport was shown. The limitation of the research, which will be explored in subsequent works, is limited

to the study of a single mode of transport, the bus. The research will need to expand to include other modes of public transport, particularly in light of developments in more recent forms of shared mobility, such as car sharing.

The next developments include the analysis of the service frequencies, the assessment of the propensity of university students to other sustainable modes of transport (e.g. car sharing) and the study of other characteristics of accessibility (e.g. Walkability).

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Anti-tampering Process for the Protection of Weapon Systems Technology in Korea

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Abstract. Korea's arms exports reached $17 billion in 2022, ranking fifth in the world. Further, Korea's defense science and technology level was ranked ninth in the world in 2020. Recently, cyberattacks targeting advanced weapon systems are on the rise, so the need to protect the technologies of defense companies while protecting the technologies of weapon systems for export is growing. In Korea, the Defense Industry Technology Protection Act, enacted in 2015, compels defense companies to build a defense technology protection system. However, the focus is only on the defense industry's technology protection system, and there is no system for protecting the weapon system technology, which is being exported, and the related research is insignificant. In this paper, we studied a weapon system anti-tampering process that can be applied to the weapon systems R&D procedure as a way to protect the defense critical technology of the weapon systems. The proposed method linked the anti-tampering process to the technical review meeting for each stage of systems engineering procedure. Also we defined the anti-tampering security level so that the target level to be implemented, and the process of determining the anti-tampering technology based on the identification of the defense critical technology and the risk assessment, and also the identification procedure for applicable anti-tampering technologies.

Keywords: Weapon Systems · Anti-tampering · System Engineering · Defense Technology Protection · Reverse-engineering

1 Introduction

Korea is independently developing advanced weapon systems and is considered the world's ninth-largest country with defense science and technology. North Korea and other hostile countries, which are directly confronting each other, are attempting to seize South Korea's defense technology, while exports of weapons systems are also increasing significantly, raising the risk of technology leakage through importing countries. In the event of an outflow to hostile countries, our weapons system may be neutralized, and if our defense technology is used by export competitors, it will be severely damaged by economic losses invested in development as well as weakened export competitiveness.

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Developed countries of national defense systematically establish protection systems for personnel, facilities, and information to protect their own researchers and technical data, and operate anti-tampering systems to prevent technology leakage of weapons systems [3]. Anti-tampering is an engineering activity to protect the technology of the weapon systems, and is to prevent leakage of technology by blocking or delaying unauthorized access to important technologies implemented in the weapon systems.

The U.S. initiated an anti-tampering system to prevent leakage of secrets and technology of weapons systems after the incident in 2001 in which China seized EP-3 of its own reconnaissance plane that landed on Hainan Island, and leaked confidential information through reverse engineering [5]. The United States is evaluating risks by reviewing vulnerabilities, threats, etc. step by step at the entire life cycle of acquiring weapons systems, and performing system engineering procedures for anti-tampering applications [4]. In addition, there is an agency dedicated to anti-tampering, and research and development of related technologies are protected in secret.

In Korea, as exports of high-tech weapons systems have recently increased and the need to protect weapon systems technology has grown, the Defense Acquisition Program Administration will first mandate the application of anti-tampering to export weapons systems. However, there are no anti-tampering guidelines yet to be applied to the acquisition of weapons systems and R&D procedures, and research in related fields is insignificant [7, 8].

In this study, we propose a process for applying anti-tampering technology to the Korea's weapon system research and development procedure. The proposed method linked the anti-tampering process to the technical review meeting for each stage of systems engineering procedure. Also we defined the anti-tampering security level so that the target level to be implemented, and the process of determining the anti-tampering technology based on the identification of the defense critical technology and the risk assessment, and also the identification procedure for applicable anti-tampering technologies.

This paper is organized as follows. Section 2 briefly introduces procedure of weapon systems research and development in Korea. Section 3 proposes Korea's anti-tampering process and Sect. 4 describes the conclusions of the paper and policy suggestions.

2 R&D Procedure for Weapon Systems in Korea

The research and development procedure for weapon systems in Korea consists of prior reserach, exploratory development, system development, and mass production. This R&D procedure conduct technical review meetings at each major stage by system engineering methdology. System engineering is a methodology that develops a system economically and balanced to meet user requirements in consideration of the life cycle perspective in all stages from user requirements to requirement analysis, design and production, verification, verification, operation, and disposal [1]. The technical review meeting is a meeting to review the completeness by comparing and analyzing the current development progress according to the requirement analysis according to the step-by-step set-up criteria at the time of official technology review [2].

Figure 1 shows the weapon system research and Development process and technical review meetings in Korea. The system engineering-based technical review meetings

consist of system requirements review (SRR), system functional review (SFR), preliminary design review (PDR), critical design review (CDR), test readiness review (TRR), functional configuration audit (FCA), and physical configuration audit (PCA).

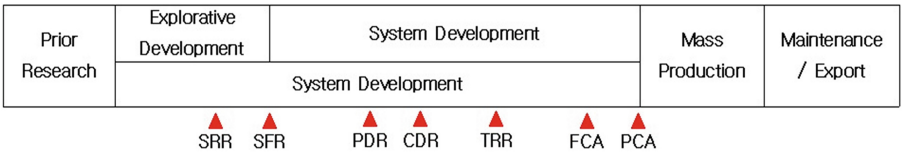

Fig. 1. Weapon Systems R&D Process and Technical Review Meetings [1]

During technical review, a baseline is set, and a baseline means a document, specification, or product baseline reviewed and agreed for shape management by development stage, and is divided into functional baseline, allocated baseline, and product baseline.

The functional baseline is a document that defines the performance, function, interoperability, and characteristics of the system/subsystem, including system specifications reflecting SFR results. The allocation baseline is a document that defines the characteristics of the development specification for the design of each feature item, such as a system/subsystem and interface reflecting the PDR results. The product baseline is a document defining the functional physical properties of a product completed as a system reflecting PCA results in the draft product specifications for prototype production reflecting CDR results [9, 10].

System Requirements Review (SRR) is performed at a time when an understanding of user requirements is completed and the results of developing major technologies and components verified through exploration and development can be reflected as weapon system requirements. Through SSR activities, all requirements included in user requirements, such as operating requirements (ORD), operational performance (ROC), and proposal requirements (RFP), should be properly converted to system/subsystem requirements, consistent and traceable by requirement.

System Functional Review (SFR) is a procedure for establishing a functional baseline for the system by ensuring that user requirements and system requirements are consistently and accurately reflected in the system standard. This procedure should be carried out before performing the initial basic design and can be performed simultaneously with SRR depending on business characteristics, but in this case, user requirements should be defined in detail and accurately as system function requirements.

Preliminary Design Review (PDR) is conducted when it is necessary to determine the completeness of the basic design and whether the Integrated Project Team (IPT) is ready to begin detailed design and testing procedures after the basic design of hardware and software products is completed.

Critical Design Review (CDR) is conducted when detailed design is completed up to detailed components/parts of the system, performance prediction is performed through M&S, and then it is necessary to determine whether prototype is ready to start.

Test Readiness Review (TRR) is a procedure to officially confirm that a test plan containing test purposes, methods, procedures, scope, manpower resources, and safety

considerations can enter the Development Test / Opeational Test (DT/OT) stage by verifying and verifying satisfaction with user requirements and system requirements.

Functional Configuration Audit (FCA) is a procedure for confirming whether the actual performance of a tangible product meets the requirements specified in the functional baseline and the allocation baseline. Physical Configuration Audit (PCA) is a procedure for determining whether the shape of the verified model matches the design document and confirming the product baseline [11–17].

3 Proposed Anti-tampering Process

3.1 Overview

The anti-tampering process is a series of activities conducted according to system engineering procedures through weapon system acquisition lifecycles, and is a risk management process for identifying, evaluating, and reviewing and implementing anti-tampering techniques.

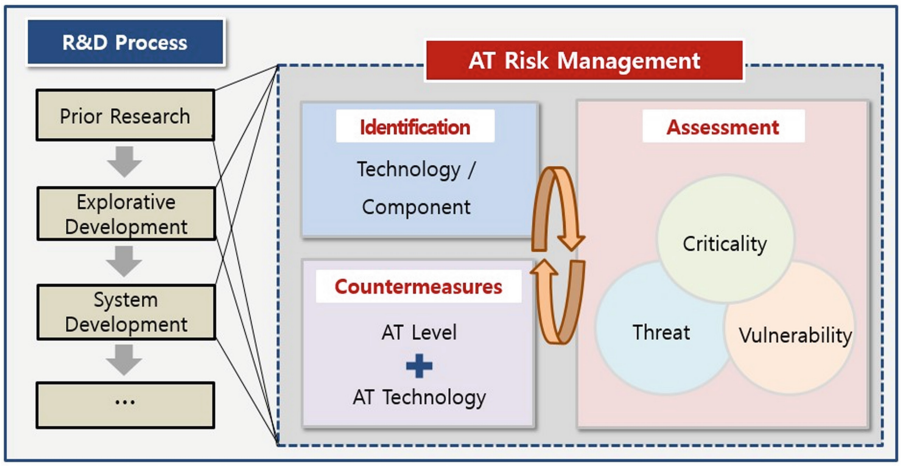

Fig. 2. Anti-Tampering Risk Management Model

Figure 2 schematically shows a proposed risk management model for anti-tampering of weapon systems. Proposed risk management should be repeatedly performed at each stage of prior research, exploration development, and system development in the acquisition life cycle. Risk management activities consist of identification of critical technologies and related components to be protected, risk assessment to analyze importance, threats, vulnerability, and review and implementation of protective measures to mitigate risk levels.

Figure 3 shows a simple schematic diagram of the entire anti-tampering process based on system engineering applied to the weapon system acquisition procedure.

The anti-tampering application process is also carried out in connection with the weapon system R&D process. The Integrated Project Team (IPT) is a control agency for

defense technology protection and must be managed from the beginning of the project. The need for protection requirement is identified from the prior research stage, and the anti-tampering protection requirements (target/grade) are clearly defined with the support of the security verification agency and provided to the R&D authority.

Based on the definition of anti-tampering requirements provided by the IPT, the R&D authority prepares the anti-tampering requirements in the anti-tampering plan (AT Plan) and reports/approves them in the Anti-Tampering Specification Review (ATSR).

For the application of anti-tampering procedures in the ATSR stage, the protection requirements (target/grade) are defined to identify the protection targets (technology/parts), update the protection level at the life cycle stage, reflect it in the AT Plan, and update the main products. After that, anti-tampering is developed and implemented, integrated into the system, and then the mass production system is integrated through a standardization process.

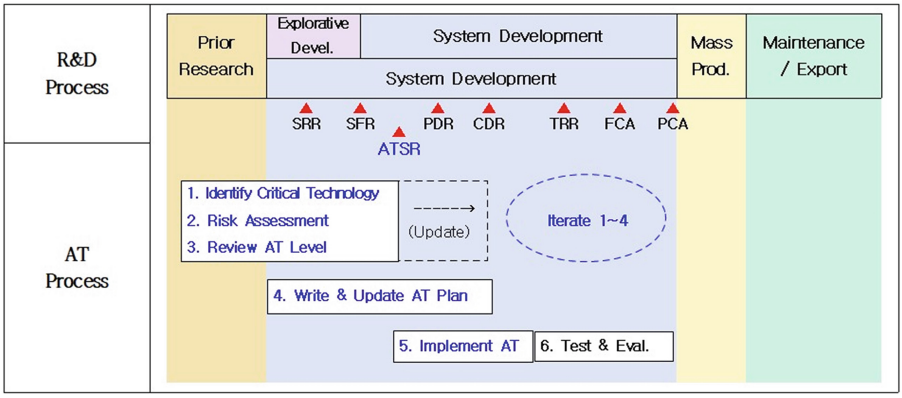

Fig. 3. Overview of anti-tampering process based on systematic engineering

In the system engineering procedures performed between weapon system R&D, the anti-tampering development procedures are system requirements review (SRR), system function review (SFR), AT requirement review (ATSR), basic design review (PDR), detailed design review (CDR), test readiness review (TRR), physical shape verification (FCA).

Among the R&D processes for each anti-tampering development stage, first, the anti-tampering requirements are analyzed in the System Requirement Review (SRR) stage. Identify the requirements for anti-tampering and devise the protection target and protection level. In the SRR phase, anti-tampering requirements are identified and an anti-tampering plan (draft) is conceived based on the anti-tampering requirements and anti-tampering requirements definitions for system performance.

In the step of Systematic Function Review (SFR), the protection targets for anti-tampering requirements are identified and the level of protection is reviewed. In the SFR stage, the anti-tampering requirements included in the system development requirement are prepared through the system function criteria, and the anti-tampering plan (draft) is

updated by reviewing the level of protection such as anti-tampering techniques based on the anti-tampering protection requirements.

The anti-tampering requirement review (ATSR) stage is proposed in this study, and based on the requirements of the anti-tampering protection level, such as anti-tampering techniques, testability, cost, and performance maintenance, etc. ATSR can be performed in combination with SFR or separately. The reason for performing ATSR separately was that it was proposed to hold an anti-tampering requirement review separately from the existing review meeting in consideration of the confidentiality of the anti-tampering design. In addition, this is because the definition of the requirements of the weapon system software can be performed separately between the system function review (SFR) and the basic design review (PDR). Anti-tampering protection consists of hardware and software and is primarily targeted at software, and software requirement analysis can be performed in the Software Specification Review (SSR) after SFR. Therefore, when defining software requirements, ATSR is performed to define and review anti-tampering requirements for software targets.

In the basic design review (PDR) stage, the HW/SW basic design for anti-tampering is reviewed. The effect on the update of anti-tampering requirements, anti-tampering design description (draft), and basic design is reviewed.

In the detailed design review (CDR) step, detailed design of H/W and S/W for anti-tampering is reviewed. Complete the final of the anti-tampering requirements, anti-tampering design techniques, anti-tampering implementation costs and problems, anti-tampering implementation activities, and AT Plan.

In the Test Preparation Status Review (TRR) stage, the test evaluation plan and preparation status are reviewed by verifying whether the anti-tampering requirements are met. In this step, the anti-tampering evaluation is planned and executed.

In the functional shape confirmation (FCA) and physical shape confirmation (PCA), the anti-tampering evaluation is supplemented and standardized by comparing the function of the shape item with the function/allocation (product) baseline.

3.2 Definition of Anti-tampering Requirements

3.2.1 Concepts and Procedures

The IPT should start activities to protect defense technology from the project preparation stage and manage anti-tampering requirements. To this end, from the stage of prior research, candidates for defense critical technology should be identified and risk assessment should be performed to define anti-tampering requirements. This definition of requirements is carried out with the support of a security verification agency (meaning a specialized institution in charge of anti-tampering of weapons systems).

The business management agency prepares the AT Requirement Definition with the support of the security verification agency. The AT requirement definition specifies defense technology candidates and AT level and is provided to R&D institutions of the project.

3.2.2 AT Level and Security Controls

When preparing an anti-tampering requirement definition, the business management agency performs a preliminary risk assessment and determines a preliminary anti-tampering level. The final anti-tampering level is determined when R&D institutions hold an anti-tampering requirement review meeting (ATSR). The anti-tampering level is repeatedly evaluated during the acquisition life cycle in consideration of the importance of the protected technology, the possibility and vulnerability of threats, and the project schedule/budget.

The anti-tampering (AT) level is consists of three levels as follows:

- A-level: Best protection
- B-level: Appropriate level of protection
- C-level: Minimum level of protection that must be applied

The anti-tampering requirements to be applied to the weapon systems consist of seven domains and security controls for each domain.

- Physical Security (PS)
- Component Security (CS)
- Cryptograph Management (CM)
- Side-channel attack Countermeasures (SC)
- Log management (LM)
- Integrity Assurance (IA)
- Account Management (AC)

Table 1 shows an overview of the anti-tampering level and requirements for each level. Required and selectively applied items are defined for each level, which means that they are recommended to be applied, but can be applied selectively in consideration of the schedule and cost of the project.

Table 1. AT requirement level and security controls

Level	Meaning	the number of security controls							
		PS	CS	CM	SC	LM	IA	AC	Total
A	Best	13	37	6	4	4	5	7	76
B	Appropriate	10	13	5	1	1	5	5	40
C	Minimum	7	-	1	-	-	-	-	8

Table 2 shows the security controls of Physical Security (PS) domain. There are thirteen security controls in PS domain. Security controls to be implemented for each AT level are defined. In the table, black circles are madatory security controls, white circles are optional, and dash is exampt for the level.

If the level A is required, eleven controls shall be implemented and two controls can be selectively implemented according to the cost and schedule of the project. However, if the level C is required, only seven out of thirteen security controls need to be implemented.

Table 2. Example: Security Controls of Physical Security (PS) Domain

Security Controls			Level		
Domain	ID	Description	A	B	C
Physical Security (PS)	PS-1	The system shall be protected with a rigid housing	●	●	●
	PS-2(1)	A pick-proof lock shall be installed on the cover or door of the cover	●	●	●
	PS-2(2)	Tamper-evidence functions, such as tampers' seals and coatings, shall be used for covers or doors of covers	●	●	●
	PS-3	A real-time detection method shall be provided when the cover or door of the unauthorized person's cover is opened. (e.g., mechanical sensors, illumination sensors, etc.)	●	●	–
	PS-4(1)	A role-based authentication method for opening the cover shall be provided. (e.g., controlling access by role by administrator, maintenance, etc.)	●	●	●
	PS-4(2)	Identity-based authentication method shall be provided for opening the cover. (e.g.,: passwords, biometric information, etc.)	●	●	●
	PS-4(3)	Multiple authentication methods shall be provided for opening the cover	○	–	–
	PS-4(4)	The authentication information for opening the cover shall be protected	●	●	●
	PS-4(5)	Authentication using the encryption module shall be provided	●	–	–
	PS-5	Physical access to external communication lines of the system shall be prevented. (prevention of eavesdropping, alteration, etc.)	●	○	–
	PS-6	Protection against electromagnetic pulse (EMP) attacks shall be provided	○	–	–
	PS-7	The tamper detection function shall be turned off when the lid of the accreditor is opened	●	●	–
	PS-8	Sensitive information (e.g., SW code, encryption key, etc.) on the system shall be erased when detecting unauthorized opening of the cover	●	●	●
	Count		13	10	7

3.3 Risk Assessment

Risk assessment analyzes the criticality, vulnerability, and threat of the protected object, and calculates the likelihood and severity of the outcome of the threat through the vulnerability.

The target of protection is defense technology and related components, and the importance of protection is evaluated by the level of mission failure in the event of technology infringement and the level of damage to national security. Vulnerability is evaluated as the severity of design weaknesses that components related to defense critical technology can be used by enemy threats (i.e., tampering attacks). Threats evaluate the likelihood of an enemy threat occurring and the likelihood of an enemy threat succeeding.

If the calculated risk level is high, protective measures to mitigate the risk should be established and implemented. In this study, protection measures were specified as AT level and requirements for each level so that R&D institutions could easily identify protection measures (Fig. 4).

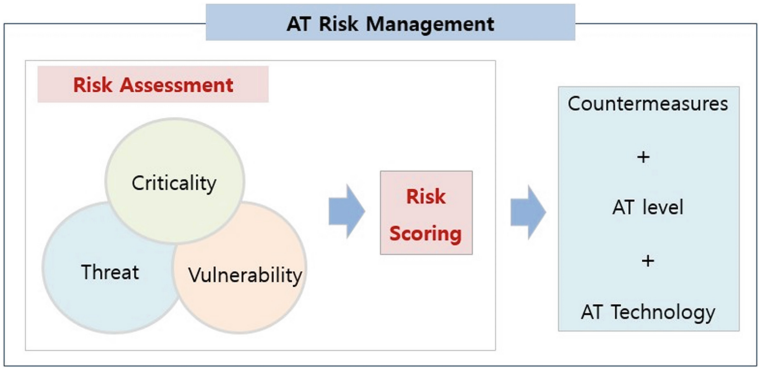

Fig. 4. AT Risk Assessment and Risk Management

Risk management starts from the prior research stage, which is the early stage of the R&D life cycle, and is updated by repeatedly identifying defense technology and implementing protection measures. The procedure for risk assessment performed by R&D institutions after the commencement of the project.

Risk evaluation is evaluated by scoring the risk level by synthesizing the results of importance analysis, vulnerability analysis, and threat analysis for defense technology and related components.

The importance analysis is analyzed by R&D agencies. Vulnerability analysis of related components is analyzed by a third professional security verification agency and also verifies that the vulnerability has been resolved when anti-tampering is applied later. Threat analysis of related components suggests a method of requesting an intelligence agency because it is necessary to analyze overseas threat information. The United States requests threat analysis to the Defense Intelligence Agency (DIA) to receive a threat analysis report. Since Korea does not have this role of intelligence agencies yet, there is a way to evaluate the threat level as high for the time being.

3.4 Determination of Anti-tampering

When the level of risk is determined to be "high (H)" for the identified defense critical technology, protection measures to lower the level of risk should be selected and implemented. In this study, anti-tampering is targeted as a protection measure. Figure 5 shows the procedure for selecting an anti-tampering technique.

The anti-tampering level required in the anti-tampering requirement definition is determined at the Anti-Tampering Requirement Review Meeting (ATSR). Anti-tampering technology that satisfies the requirements of the confirmed anti-tampering level should be designed and implemented. Mandatory requirements must be applied, and optional requirements are reviewed in consideration of costs, schedules, etc.

For the implementation of each anti-tampering requirements, the best technology should be selected by identifying anti-tampering technologies capable of various anti-tampering technologies and compromising analysis of cost, schedule, and system performance.

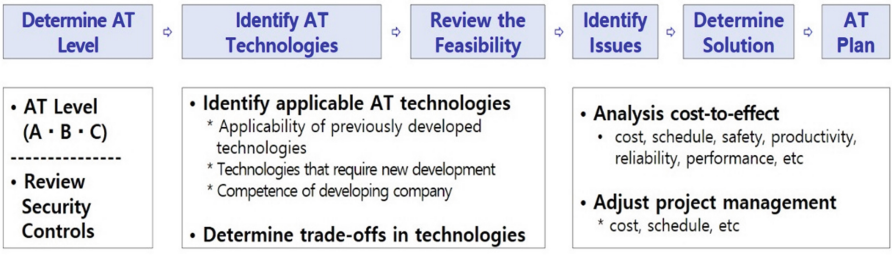

Fig. 5. Procedures for Selecting Anti-tampering Technology

The AT level and the respective security controls are reviewed. AT technology is selected by analyzing each technology by identifying applicable AT technology for each requirement and reviewing whether the applicable technology is negotiable.

4 Conclusion

This study proposed an anti-tampering process for weapons systems that can be applied to Korean defense R&D procedures. The proposed anti-tampering process is carried out in accordance with system engineering procedures, defining the work procedures and activities to be carried out at each technical review meeting, and defining the output. Major proposed anti-tampering activities include defining anti-tampering requirements, identifying defense critical technologies to be protected, risk assessment, and selection of anti-tampering techniques.

In the absence of anti-tampering systems and guidelines to be applied to weapons system R&D procedures in Korea, we propose policies for the development of the anti-tampering system as follows.

First, it is necessary to systematically establish a system through the designation or establishment of an agency dedicated to anti-tampering and support the development

of anti-tampering by defense companies. The U.S. has a dedicated agency under the Defense Ministry to support anti-tampering of defense companies. In addition, intelligence agencies such as the Defense Intelligence Agency (DIA) also analyze threat information about weapon system technology to support the decision to apply anti-tampering [16].

Second, the anti-tampering guidelines for weapons systems should be developed under the Defense Acquisition Program Administration Directive or regulations and provided to defense companies and defense science research institutes. Currently, the defense technology protection guidelines focus on protecting R&D data of defense companies [6], and there is no content for anti-tampering, so guidelines to be applied in weapons system R&D are urgently needed.

Third, it is necessary to establish a system in which defense companies and defense science research institutes build and share defense technology information as a database for consistent identification of defense technology. Anti-tampering is to protect the defense technology of weapons systems, and basically, consistent identification of defense technology should be preceded. However, it is currently difficult to apply consistent anti-tampering techniques due to different identification criteria for each defense company, so standard identification should be supported by sharing defense technology information.

The limitation of this study is that it was not applied to the actual weapons system development project and theoretical research was conducted. Therefore, it is necessary to establish a process by analyzing and researching in-depth anti-tampering process application cases or data not covered in this paper, and to apply them to actual weapons system R&D projects.

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BTIMFL: A Blockchain-Based Trust Incentive Mechanism in Federated Learning

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Abstract. Federated learning (FL) is a machine learning technique that allows multiple devices to train a model collaboratively without sharing their data with a central server. It has advantages such as increased privacy, reduced communication costs, and improved scalability, making it useful in scenarios where data is distributed across multiple devices and privacy is a concern, such as in healthcare or finance. However, the potential for participants to behave selfishly in FL can be a challenge, and incentive mechanisms are needed to encourage them to participate in the training process. Incentives can take many strategies, such as financial rewards or reputation-based systems, and can be tailored to specific needs. In defense technology, FL can be used for predictive maintenance, target recognition, and intelligence analysis. However, the existing incentive mechanisms in FL have limitations, such as being complex to design and implement, and raising privacy concerns. To improve the incentive mechanisms in FL, we propose an incentive mechanism based on blockchain called BTIMFL that ensures transparency and effectiveness. The proposed mechanism includes DAO (Decentralized Autonomous Organizations) and smart contracts for the automatic distribution of profits to ensure fairness.

Keywords: Blockchain · DAO (Decentralized Autonomous Organizations) · Federated Learning (FL) · Inventive Mechanism · Smart Contracts

1 Introduction

Federated learning (FL) is a machine learning technique that allows multiple devices to collaboratively train a model without having to share their data with a central server [1–6]. Instead of sending data from individual devices to a central location for analysis, FL allows the data to remain on each device, while the model is sent to each device for training [4, 7, 8]. The updated model weights are then sent back to a central server where they are aggregated and used to improve the model. It has several advantages, including increased privacy for the data owners, reduced communication costs, and improved scalability. It is especially useful in scenarios where data is distributed across multiple devices and cannot be easily transferred to a central location for analysis, such as in the case of mobile devices, Internet of Things (IoT) devices, or healthcare devices [9–11]. It can also be used in cases where data privacy is a concern, such as in the medical or financial industries [5].

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Incentive mechanisms are important in FL because they encourage participants to contribute their data and computational resources to the FL process. Since FL involves training models on data that is distributed across multiple devices, it is important to incentivize these devices to participate in the training process proactively [6, 12, 13]. A key challenge with FL is the potential for participants to behave greedily, either by refusing to contribute their data or by intentionally sending incorrect data to the central server [5]. Incentive mechanisms can be used to address these challenges by rewarding participants for contributing high-quality data and penalizing them for misbehavior [5]. Effective incentive mechanisms can help ensure that participants have an incentive to contribute to the FL process and are motivated to do so in a way that benefits the overall training objective [5, 6]. Incentives can take many forms, such as financial rewards, reputation-based systems, or other forms of recognition, and they can be tailored to the specific needs of its application. Especially, in defense technology, FL can be used for a variety of purposes. In the defense industry, predictive maintenance is critical to ensuring that equipment and machinery are operating efficiently and effectively. FL can be used to train predictive maintenance models on distributed datasets from different units, enabling better predictions and maintenance scheduling. It can also be used for target recognition in defense applications. For example, drones equipped with cameras can collect images of potential targets, which can be analyzed and classified using federated learning algorithms. The models can be trained on distributed datasets from different drones, improving the accuracy of target recognition while preserving data privacy. FL may help to train models for intelligence analysis, such as natural language processing models for analyzing text data. It can be used to analyze distributed datasets of intelligence reports, enabling better insights while preserving the privacy of sensitive data. Overall, FL has great potential in defense technology applications, enabling better machine learning models while preserving data privacy and security. In summary, incentive mechanisms are important in FL because they help address the challenges of data distribution and self-interested behavior among participants, and they can help ensure the success of its process. Therefore, a lot of studies have performed to design incentive mechanism for operated FL effectively.

It is identified that the existed incentive mechanism in FL has some limitations that should be solved. First, incentive mechanisms can be expensive to implement, particularly if they involve financial rewards or other forms of compensation [14]. The cost of implementing these mechanisms can sometimes outweigh the benefits, particularly if the FL project is relatively small or has limited resources. Secondly, incentive mechanisms can be complex to design and implement, particularly if they involve a large number of participants or require sophisticated algorithms to calculate rewards or penalties [9]. This complexity can make it difficult to ensure that the incentives are fair, transparent, and effective [15]. Third, it raises privacy concerns, particularly if they involve the exchange of sensitive information or the tracking of participant behavior [16, 17]. It can generate a refuse of participation with privacy concerns, which may be difficult to resolve. It is important to carefully consider the potential limitations and tradeoffs involved in implementing FL successfully [18]. Therefore, this study suggests the incentive mechanism with adopting blockchain (i.e., BTIMFL) for improving its transparency and effectiveness compared to existing incentive mechanism.

The main contributions of this paper are as follows: 1. We comprehensively consider prior research on incentive mechanisms adopted by FL to derive features and improvements. 2. To improve incentive mechanism of FL, we propose an incentive mechanism based on blockchain. The decentralization of the blockchain cannot be tampered with, so it can prevent the local model parameters from being tampered with and affecting the overall model performance. 3. We suggest an incentive mechanism based on smart contracts and DAO (Decentralized Autonomous Organization). Participants who contribute to the model will be rewarded to ensure the sustainable development of FL. To ensure the fairness of incentives, we have designed a smart contract for the automatic distribution of profits on the blockchain that avoids the participation of third parties.

2 Related Works

2.1 Federated Learning

FL is a new distributed machine learning technique that allows multiple devices or machines to collaboratively train a model without sharing their data with each other [2, 3, 8, 19]. In FL, a central server coordinates the learning process, but the data remains on the local devices such as smartphone [17, 18]. The devices perform the computation on their own data and then send the model updates to the central server [2, 17]. The central server aggregates these updates to create an improved global model, which is then sent back to the devices to be further refined [8, 19].

FL allows for the training of models without centralizing sensitive data [20]. It has been developed to address the privacy concerns associated with centralized machine learning [14, 20]. In traditional machine learning, data is centralized on a server, and the model is trained, however, centralized data on a server raises privacy concerns since the data may contain sensitive or personal information [1, 19]. Additionally, transmitting large amounts of data to a centralized server may increase the risk of data breaches [18]. The most data have no choice but to be stored across multiple devices or locations, making it difficult or impossible to avoid centralize the data for training [2, 18]. FL can enable training on edge devices, where the data is generated, reducing the need for centralized computation [19]. It is well-suited for cases where the data is sensitive or where the data volume is too large to be sent to a centralized server for training.

FL is a rapidly evolving area of research and is being applied in many fields, including finance, healthcare, and natural language processing. FL has been used in mobile device applications to improve predictive text, auto-correction, and voice recognition. For example, the Google keyboard (Gboard), uses FL to personalize typing suggestions based on the user's writing style [14]. It also has been used in healthcare to develop models for diagnosing diseases, predicting outcomes, and identifying potential drug targets. Researchers have used FL to train models for detecting diabetic retinopathy by aggregating data from different healthcare institutions without centralizing patient data [20].

FL is widely adopted not only for privacy-preserving, but also for scalability and efficiency. FL enables the training of models using decentralized computing resources, which makes it possible to scale machine learning to massive datasets [21, 22]. By training models locally, FL can reduce the need for large centralized data storage and

processing and large amounts of data to be transmitted to a central server, which can save time and resources [23, 24]. In other words, it can improve efficiency by saving time, bandwidth, and computing resources.

FL is a rapidly evolving research area with many developments and opportunities and recent research trends are summarized as follows. First, privacy and security is the main challenges of FL which ensure the data privacy and security. Recent research has mainly focused on developing techniques for secure aggregation, differential privacy (DP) [25–27], and homomorphic encryption (HE) [16, 28, 29] to protect the privacy of user data while allowing for effective model training. Second, FL often requires communication between devices, which can be a bottleneck in the training process. It can result in increased latency, network congestion, and reduced model training efficiency when dealing with large amounts of data [23, 30]. Therefore, recent research has focused on securing communication-efficient algorithms with developing algorithms that minimize communication overhead while still achieving high model accuracy. For example, to reduce the communication overhead by aggregating global model only when the global model's weight differed by some selected threshold is suggested [8]. Third, FL can be applied to a wide range of data sources, including text, images, audios, and sensor data. Almost, FL algorithms assume that data is homogeneously distributed across devices, however, the data may be highly heterogeneous, in real-world, which can lead to issues such as imbalanced datasets, noisy data, and biased training [31, 32]. It addresses the needs for exploring the challenges of training models on heterogeneous data sources and develops techniques for adapting models to different types of data. To mitigate the effect of non-independent and non-identically data, a feature fusion approach by aggregating local and global model is presented [33]. Similarly, it is designed to form clusters of clients based on the geometrics properties of the FL surface with jointly trainable data distribution. Fourth, FL systems are vulnerable to various attacks, such as poisoning attacks, model inversion attacks, and membership inference attacks [34–36]. Therefore a few studies have focused on developing algorithms that are robust to attacks.

2.2 Incentive Mechanism for Federated Learning

Incentive mechanisms are used in FL to incentivize the participants to contribute their data and computational resources to the training process. Without proper incentives, participants may not be willing to contribute their resources, leading to a lack of participation and finally, lower model performance [1–3, 8, 19, 24]. The importance of incentive mechanism in FL can be summarized as follows. First, in FL, it may collect varied computational resources of participants. Participants may be unwilling to share those resources without proper incentives because they have limited computational resources [2]. Secondly, recent users have be-gun to perceive the 'data ownership' of the data they have generated or data about themselves (i.e., personal information) and consider it as their own property. There-fore, participants may be reluctant to share it without proper incentives, which could result in a limited and biased dataset [37, 38]. It can help increase participation in the training process by providing participants with an incentive to contribute their high-quality data [1, 3]. An incentive mechanism can finally encourage participants to contribute high-quality data, leading to higher model performance. Third, incentive mechanisms can help ensure that participants are compensated fairly

for their contributions [4, 9]. This can help prevent participants from feeling exploited and can lead to greater participation in future training rounds [39]. Overall, incentive mechanisms are important in FL because they can help to promote greater participation, higher-quality contributions, and better privacy and security protections for participants. It is possible to achieve the desired outcomes while minimizing negative impacts on participants by designing incentive mechanisms effectively.

Based on the importance of the incentive mechanism in FL, a few studies have designed it with considering the following principles: fairness, privacy, transparency, flexibility. Incentive mechanisms should be designed to be fair to all participants. It means that the rewards should be proportional to the contributions made by each participant and should not unfairly favor any participant or groups. Incentive mechanisms also should not compromise the privacy or security of the participants' data. Participants understand how the rewards are estimated and what they need to do to earn them by securing its transparency. It can help to build trust and encourage participation. Incentive mechanisms has to be flexible, so that they can adapt to changing conditions or goals. The rewards should be adjustable based on the needs of the system and should not be fixed or static.

The goal of embedding incentive mechanism is to motivate participants to contribute in FL and improve the performance of it. The optimal strategy of each participant and the reward of the server are determined through solving the optimization problems (e.g., social welfare maximization problem) in the incentive mechanism. The reward paid to each participant is allocated according to the contribution measurement, node selection and payment allocation with three phase levels [10]. The objective of contribution measurement is to fairly evaluate each participant's contribution to FL training performance, which includes various resources beyond just training data [40]. Node selection involves choosing a subset of participants with enough resources that fit within the system's budget constraints. It is important to consider different types of resources to ensure efficient training, as a participant with low computing power and ample data may cause delays [41]. Payment allocation involves deciding how to distribute payments to participants, which may include money, usage of the global model, and other rewards. Payment allocation problems are difficult to solve, and it is essential to find efficient solutions [7]. These components should be interdependent [10]. A lot of studies adopted various economic and game theoretic approaches to design incentive mechanism, including Stackelberg game, Shapley value, auction, contract theory, and reinforcement learning.

Stackelberg Game. Stackelberg game can be used to incentivize participation in FL by providing additional rewards or benefits to the first mover or leader [10]. By encouraging a leader to initiate the learning process and share the learned model with others, Stackelberg game can promote cooperation and participation among other entities [42]. It assumes that there is a clear distinction between the leader and the followers, which may not be applicable in all FL scenarios [10]. Additionally, the leader may not always act in the best interest of the overall learning process, particularly if their incentives are misaligned with the goals of the others [10].

Shapley Value. Shapley Value can be adopted to determine the fair allocation of rewards among participating entities based on their contributions to the overall model accuracy in FL [10, 11]. Shapley Value provides a way to fairly distribute rewards and incentivize participation by considering the marginal contribution of each entity [5]. It assumes that

the contributions of each entity are independent and additive, which may not always be the case in FL [9]. Computing the Shapley Value can be computationally expensive, in scenarios with a large number of participating entities.

Auction. Auction mechanisms can be applied with incentive mechanism to allocate resources such as computation or communication bandwidth among participating entities. By creating a competitive environment, auction mechanisms incentivize entities to bid for resources and provide accurate model updates in exchange for higher rewards [10]. Auction mechanisms require a clear and well-defined set of resources to be auctioned, which may not be feasible in all FL scenarios. The auction process can be vulnerable to manipulation or collusion by participating entities, which can compromise the fairness of the allocation.

Contract Theory. Contract theory can be used to design incentive mechanisms in FL that align the interests of participating entities with the overall goals of the learning process [5]. To create contracts that specify the rewards and penalties for different behaviors, contract theory can incentivize entities to behave in ways that maximize the overall learning performance [1, 6, 13]. Contract theory assumes that there is a clear and complete understanding of the learning process and the behavior of participating entities, which may not always be the case in FL [10, 24]. To design contracts that incentivize desirable behavior while avoiding unintended consequences can be challenging [6].

Reinforcement Learning. Reinforcement learning can be applied to design adaptive incentive mechanisms in FL that learn and adjust based on the behavior of participating entities [9–11]. By modeling the learning process as a reinforcement learning problem, incentive mechanisms can be designed to encourage entities to behave in ways that maximize the overall learning performance over time [3, 11]. Reinforcement learning requires a well-defined objective function and reward signal, which may not be straightforward to specify in all FL scenarios [10]. Designing an incentive mechanism based on reinforcement learning that balances exploration with attempting to discover new features by a selecting sub-optimal action and exploitation of using what we already know to get the best results we know of can be difficult [43].

The recent limitations of incentive mechanisms in FL is the challenge of designing it that are resistant to various types of attacks and malicious behaviors. One of the major examples is the "free-riding" problem, where some entities may withhold their data or provide low-quality updates in order to receive the benefits of FL without incurring the costs of participation [44]. Incentive mechanisms need to be designed in a way that encourages participation and contribution from all entities, while also detecting and penalizing free-riding behavior. Another challenge is ensuring the privacy and security of data in FL. Incentive mechanisms need to be designed in a way to ensure the participating entities are not able to access or manipulate sensitive data, while still providing appropriate incentives for collaboration. Finally, there is a need for incentive mechanisms that can adapt to changing conditions and dynamics in FL [5, 13]. For example, as the number and distribution of participating entities changes over time, incentive mechanisms need to be able to adjust the rewards and penalties to maintain a balanced and effective learning process [10]. Addressing as we mentioned and other recent limitations will require continued research and development in the design of incentive mechanisms

for FL, as well as the integration of techniques from areas such as privacy-preserving machine learning, game theory, and distributed systems.

3 Proposed Model

Designing incentive mechanisms in FL using blockchain technology can provide several benefits, such as increased transparency, accountability, and security [14, 18, 22, 45]. Recent studies have explored the use of blockchain in FL for designing incentive mechanisms and some of the key findings could be summarized as follows. First, blockchain can enable decentralized governance mechanisms for FL incentive design. Qu, Gao, Luan, Xiang, Yu, Li and Zheng [46] proposed a blockchain-based governance framework for FL that incorporates reputation-based incentives about reward distribution. Second, blockchain can facilitate privacy-preserving incentive mechanisms in FL [14, 22]. A recent study suggested a blockchain-based framework that uses secure multi-party computation (MPC) to compute rewards without revealing sensitive data [47]. Third, blockchain can enable token-based incentives in FL, where participants are rewarded with cryptocurrency tokens for their contributions and inspire their proactive participants [48]. A token-based incentive mechanism for FL is suggested that leverages smart contracts to enforce rewards and penalties [49, 50]. Fourth, blockchain can support game-theoretic incentive mechanisms in FL. Finally, blockchain can enhance fairness and transparency in FL incentive design. A blockchain-based mechanism that uses fairness measures to ensure that rewards are distributed equitably among participants, while also providing transparency through a public ledger of reward transactions [14, 17, 18, 22, 45, 46, 50]. Overall, these studies demonstrate the potential for blockchain to enhance incentive mechanism design in FL, by enabling decentralized governance, privacy-preserving incentives, token-based rewards, game-theoretic mechanisms, and increased fairness and transparency. However, there is still much research to be performed to fully consider the opportunities and challenges of using blockchain in FL incentive design. Therefore, this study considers the principles of 'smart contracts', 'decentralized governance', 'reputation-based incentives' to design incentive mechanism based on blockchain.

Smart Contracts. Smart contracts can create automated agreements between participants in FL [51, 52]. For example, a smart contract could specify the terms of a data sharing agreement, including the rewards and penalties for each participant based on their contributions. The use of blockchain can ensure that the terms of the smart contract are enforced in a secure and transparent way [50].

Decentralized Governance. Blockchain-based governance (i.e., DAO) mechanisms can be used to ensure that participants have a authority in the decision-making process of the FL system [14]. DAO could be created to manage the incentives and rewards for FL participants [53]. It can ensure that the governance process is transparent and democratic, with each entity having an equal authority in the decision-making process.

Reputation-Based Incentives. Participations are rewarded based on their reputation or track record of providing accurate and high-quality updates [1, 54]. Reputation scores

are maintained in a secure and transparent manner, with each update being recorded on the blockchain [55].

Based on those above-mentioned principles, we suggest the incentive mechanism based on blockchain with trust, called BTIMFL. It fulfills the goals of operating an incentive mechanism with trust: 1) estimating reasonable rewards to all participants and operators of FL, 2) encouraging voluntary participation, and 3) fair distribution of rewards. BTIMFL promotes transparency and fairness in the measurement of rewards for participants based on the operating model of DAOs unlike the mechanisms proposed in the past. In other words, if the existing incentive mechanisms exclusively operate the calculation of rewards on a central server and distribute rewards from the top-down, BTIMFL not only provides data and resources to the FL the moment participants decide to participate in the FL, but also acts as a decision-making entity to evaluate the objectivity of the reward calculation.

In BRIMFL, the specific incentive reward design and distribution process is as follows: First, a user who participates in the FL has the obligation to provide data and resources, as well as the right to be provided incentives for what they provide; second, before providing data and resources, the participant transmits to the block-chain server the amount the participant wants to be compensated for. Third, all participants will view the estimated rewards of all participants through the blockchain and vote on the appropriateness of each reward. Fourth, for each FL, only participants who are approved according to the pre-agreed ratio of votes passed will provide the data and resources they have presented in advance. Fifth, when a participant's data and resource is provided, a ratio of the reward which was consented is sent to each participant according to the smart contract. Finally, the participant who received the reward will receive the entire remaining incentive if the participant is evaluated through the blockchain-based reputation system as a participant who has fulfilled all the pre-agreed conditions, rather than a free rider or a node with negligence of duty.

4 Conclusion

A novel incentive mechanism (i.e., BTIMFL) based on reputation points has been created by combining FL and blockchain technology. The main objective of this study is to establish a trustworthy environment for participation and an automated revenue sharing mechanism. To prevent malicious nodes from causing damage to the global model parameters, this incentive mechanism incorporates reputation points. Nodes with low reputation points are identified as malicious and prohibited from sharing or incorporating in a global model, thereby protecting the global model. It allows more enthusiastic participants to join the federated ecosystem. The increase in data volume enhances the model's effectiveness and enables participants to receive more benefits, resulting in a mutually beneficial outcome with achieving a win-win situation.

This research provides the following future research directions. First, we will verify how the incentive mechanism proposed in this study improves FL operations compared to existing incentive mechanisms from a comprehensive perspective of privacy, communication cost, and scalability. Second, we will further design incentive mechanisms from the perspective of VFL (vertical federated learning) and cross-device. Most of

the existing research on incentive mechanisms is centered on the server to utilize the client's resources with minimal incentive cost in a perspective of cross-silo. Therefore, based on the incentive mechanism proposed in this study, we plan to investigate continuously how to improve a fair and reasonable reward/evaluation system for voluntary client participation in FL in future studies.

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Area-Efficient Accelerator for the Full NTRU-KEM Algorithm

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Abstract. Among Post Quantum Cryptography (PQC) algorithms, Nth-degree Truncated-polynomial Ring Units Key Encapsulation Mechanism (NTRU-KEM) emerged as a promising cryptosystem for key establishment. However, the algorithm requires more storage space and computation resources compared to classical cryptosystems, resulting in substantial memory and performance overheads. To mitigate these overheads, researchers have focused on enhancing the efficiency of the NTRU-KEM algorithm with dedicated hardware implementation, but have excluded the key generation function, resulting in a tenfold increase in latency when generating new keys frequently. In this paper, we aim to implement an efficient NTRU-KEM algorithm with full functionality by incorporating all functions, including key generation, using a hardware and software co-design approach. We strategically allocate functions based on their inherent parallelism and execution time to hardware or software. Our approach entails implementing hardware modules to be shared across multiple sub-functions as much as possible to achieve optimal performance improvement over hardware resources. Our implementation demonstrated a significant speedup compared to pure software implementation in the execution time of all three functions of NTRU-KEM, with a remarkable performance improvement in key generation. Our approach resulted in more than three times the area reduction effect compared to prior work focused only on encapsulation and decapsulation functions, and showed similar or better results of performance per area depending on the function.

Keywords: NTRU · Post Quantum Cryptography · Hardware Accelerator

1 Introduction

Recently, quantum computing has emerged as a prime interest due to its potential to providing significant benefits to society in virtue of its capability to accelerate workloads compared to classical computing. As lots of research on quantum computing show great development, however, security issues were raised

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since the conventional cryptosystems used in classical computing are not resistant to quantum computing. In particular, previous research has demonstrated that classical methods of key establishment [9,17] are susceptible to compromise through quantum computing [20]. As a counter measurement, new algorithms have been developed to withstand cryptoanalytic attacks facilitated by quantum computing. These algorithms are collectively referred to as Post Quantum Cryptography (PQC). Out of several PQC algorithms that facilitate key establishment, Nth-degree Truncated-polynomial Ring Units (NTRU) [11] has emerged as a particularly promising cryptosystem. Notably, since its introduction in 1996, NTRU has yet to be compromised [1]. In lieu of classical key establishment algorithms, NTRU employs a Key Encapsulation Mechanism (KEM), which utilizes an asymmetric key to encrypt a symmetric key (e.g., session key) to facilitate its transmission for key establishment.

Sadly, like other PQC algorithms, NTRU-KEM necessitates increased storage space and computation resources relative to classical cryptosystems. Consequently, the adoption of NTRU-KEM in current systems results in substantial memory and performance overheads. To mitigate these overheads, researchers have conducted studies [2,10,15] focused on enhancing the efficiency of the NTRU-KEM algorithm with regard to storage and performance through dedicated hardware implementation. These studies generally concentrate on the encapsulation and decapsulation functions, which represent two of the three functions comprising the NTRU-KEM algorithm. They exclude the third function, key generation (`KEYGEN`), claiming the key can be generated in advance and stored in memory for repeated uses. This approach, however, confines the implementation of NTRU-KEM to a long-term key scenario. To enable the utilization of NTRU-KEM in a session-key context, wherein new keys must be generated frequently, prior research has been compelled to rely on software to execute `KEYGEN`, which results in a tenfold increase in latency relative to encapsulation and decapsulation combined.

Based on our observation, we have opted to incorporate all functions, including `KEYGEN`, in our endeavor to implement an efficient NTRU-KEM algorithm with full functionality. To achieve this goal, we have adopted a hardware and software co-design methodology in this paper, a well-established platform utilized by a multitude of PQC algorithm accelerators [12,18]. Our decision to utilize this approach is based on its proven effectiveness in addressing the challenges encountered in implementing the NTRU-KEM algorithm, including the significant performance overheads associated with conventional software-based `KEYGEN` implementation. Through the adoption of a hardware and software co-design approach, we seek to enhance the efficiency of NTRU-KEM by simultaneously leveraging the strengths of both hardware and software components.

Our implementation aimed to achieve optimal performance improvement over hardware resources by strategically allocating functions based on both their inherent parallelism and execution time to hardware or software. Specifically, functions that exhibit high inherent parallelism and consume a large portion

of execution time were implemented into hardware to harness the full potential of available hardware resources and achieve significant performance gains. Conversely, functions that either predominantly involve sequential operations or consume a small portion of execution time were implemented into the software. This approach allows us to avoid expending unnecessary hardware resources that could have otherwise been allocated to other functions exhibiting the potential for achieving markedly enhanced levels of performance. We describe our implementation in detail in the following Sects. 3, 4.

To demonstrate the efficiency of our implementation, we targeted the hardware part of our design onto a 45 nm process technology with a clock frequency of 1 GHz. Meanwhile, the software part was targeted to a Cortex M4(STM32F407VG), operating at 168 MHz of clock frequency. In our experiment, our implementation demonstrated a speedup of 579× in the average execution time of all three functions of NTRU-KEM, as compared to a pure software implementation. In particular, our implementation of `KEYGEN` has demonstrated a remarkable performance improvement over software-only implementation, as evidenced by a factor of 1,393 times faster. This finding underscores the significant practical value of our approach, especially in situations where frequent key generation is required. Compared to prior work [2] that solely focused on encapsulation and decapsulation functions excluding `KEYGEN`, our implementation stands out as more efficient in terms of hardware resources. Specifically, ours shows an area reduction of 29,821 μm^2, while offering a performance per area that exceeds the prior by a factor of 1.5.

2 Background

This section provides a brief introduction to the fundamentals of NTRU-KEM algorithm, as well as lattice-based cryptography as the theoretical basis of NTRU.

2.1 Lattice-Based Cryptography

Lattice-based Cryptography refers to a cryptosystem constructed over mathematical grounds that involves lattices in the security proof. They are currently widely used for PQC and other cryptosystems, including NTRU. A lattice $\mathcal{L}(\mathbb{B})$ in an n-th dimension refers to the end-points of vectors that can be formed by linear combinations of a given basis $\mathbb{B} = (b_1, b_2, \ldots, b_n)$. The security guarantees of cryptosystems over lattice are bound to hardness from problems such as the Shortest Vector Problem or Closest Vector Problem. In several cryptosystems, such n-th dimension vectors are interpreted as polynomials bound in integer rings. Lattice-based encryption schemes are constructed by adding a random lattice point to a plaintext vector, and the resulting ciphertext is sent to the receiver, who decrypts it using their private key to find the lattice point closest to the ciphertext. Lattice-based cryptography is resistant to quantum attacks due to the hardness of underlying problems, even for quantum computers, which makes it advantageous over other public-key cryptosystems. Furthermore, the

KeyGen(*seed*)	Encapsulate(**h**)	Decapsulate((**f**, $\mathbf{f}_p$, $\mathbf{h}_q$, s), **h**)
1. ((**f**, $\mathbf{f}_p$, $\mathbf{h}_q$), **h**) ← KeyGen′(*seed*)	1. *coins* ←$_{\$}$ $\{0, 1\}^{256}$	1. (**r**, **m**, *fail*) ← Decrypt((**f**, $\mathbf{f}_p$, $\mathbf{h}_q$), **c**)
2. s ←$_{\$}$ $\{0, 1\}^{256}$	2. (**r**, **m**) ← Sample_rm(*coins*)	2. $k_1 \leftarrow H_1(\mathbf{r}, \mathbf{m})$
3. return ((**f**, $\mathbf{f}_p$, $\mathbf{h}_q$, s), **c**)	3. **c** ← Encrypt(**h**, (**r**, **m**))	3. $k_2 \leftarrow H_2(s, \mathbf{c})$
	4. $k \leftarrow H_1(\mathbf{r}, \mathbf{m})$	4. if $fail = 0$ return k_1
	5. return (**c**, k)	5. else return k_2

Fig. 1. The Three Functions of NTRU-KEM

efficiency properties of lattice-based cryptographic schemes make them suitable for resource-constrained environments like the Internet of Things (IoT).

2.2 NTRU Cryptosystem

NTRU is a latticed-based public-key cryptosystem that was first introduced in 1996 [11]. NTRU cryptosystem is based on operations between polynomials over integer quotient rings $R_q = Z_q[x]/(x^n - 1)$, $S_q = Z_q[x]/\Phi_n$, and $S_p = Z_p[x]/\Phi_n$, where n and p are prime integers and q is coprime with both p and n while $p << q$, $\Phi_1 = x - 1 \in \mathbb{Z}[x]$ and $\Phi_n = x^{n-1} + x^{n-2} + \cdots + x + 1 \in \mathbb{Z}[x]$. The coefficients of R_q and S_q are encoded in two's complement modulo q. The existing variants of NTRU [11] use $p = 3$, which leads rings and polynomials to have coefficients using 2 bits, -1, 0, or 1. Let Γ be the set of ternary polynomials in $\mathbb{Z}_3[x]/(x^n - 1)$ with at most $n - 2$ degrees of order. NTRU cryptosystem samples 4 polynomials, f, g, r, and m from Γ, which are used as will be described in Sect. 2.3.

2.3 NTRU-KEM Algorithm

NTRU-KEM consists of three functions, `KEYGEN`, Encapsulation, and Decapsulation. `KEYGEN` generates a key pair $K_{priv} = (f, f_p, h_q)$ and $K_{pub} = h$. The process starts by sampling the four polynomials and then computing $f_p = f^{-1}\ mod(3, \Phi_n)$ and $f_q = f^{-1}\ mod\ (q, \Phi_n)$. The publickey h is a polynomial in R_q calculated from $h = (3 \cdot g \cdot f_q)\ mod\ (q, x^n - 1)$. The last component of the private key, h_q, is a pre-computed polynomial $h_q = h^{-1}\ mod\ (q, \Phi_n)$. Using the polynomials above, encapsulation and decapsulation are computed as depicted in Fig. 1.

3 Design Choices

In this section, we present the design choices we have made to optimize the performance of the three main functions of NTRU-KEM, namely encapsulation, decapsulation, and `KEYGEN`. We have carefully considered various approaches to improve the efficiency of these functions, and we will elaborate on these design choices in detail.

3.1 Selecting Sub-functions for Acceleration

In the context of hardware acceleration, the process of choosing a specific sub-function to be optimized and sped up through hardware is an essential task that

Table 1. NTRU-KEM Profiling Results

Function	NTRU Variant							
	HPS2048509		HPS2048677		HPS4096821		HRSS701	
Key Generation	3489.32 ms	100%	6094.56 ms	100%	9164.47 ms	100%	6702.06 ms	100%
poly_Rq_inv	1663.96	45.92	2891.57	46.77	4317.10	46.71	3152.91	46.87
poly_R2_inv								
poly_R2_inv_to_Rq_inv								
poly_S3_inv	1564.79	43.19	2633.54	42.59	3961.83	42.86	2881.90	42.84
poly_Rq_mul	382.57	10.55	642.18	10.38	944.20	10.21	688.49	10.23
crypto_sort_int32	8.07	0.22	11.49	0.18	14.59	0.15	-	-
randombytes	3.56	0.09	3.63	0.05	4.03	0.04	3.36	0.04
Encapsulation	92.10 ms	100%	157.91 ms	100%	211.15 ms	100%	160.61 ms	100%
poly_Rq_mul	79.97	85.94	139.72	88.48	198.80	89.89	157.98	97.84
crypto_sort_int32	9.44	10.15	13.87	8.78	17.61	7.96	-	-
randombytes	3.34	3.59	3.84	2.43	4.15	1.88	3.08	1.91
etc	0.28	0.30	0.46	0.29	0.57	0.26	0.39	0.24
Decapsulation	233.21 ms	100%	418.95 ms	100%	603.89 ms	100%	452.73 ms	100%
poly_Rq_mul	76.03	32.48	136.59	32.53	200.52	33.21	146.80	32.52
poly_S3_mul	78.54	33.55	141.09	33.60	201.20	33.32	151.64	33.59
poly_Sq_mul	78.54	33.55	141.09	33.60	200.68	33.24	151.65	33.58
hash	0.92	0.39	1.06	0.25	1.30	0.21	1.31	0.29
etc	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00

needs to be done first. In order to identify the specific sub-functions that have the potential to significantly reduce the overall execution time of NTRU-KEM, a comprehensive profiling analysis was conducted on four distinct variants of NTRU-KEM with different parameter configurations. This process involved a detailed examination of the performance characteristics of each sub-function, with the aim of determining which ones may be optimized for improved efficiency. We used the NIST submission version of NTRU-KEM with a Cortex M4(STM32F407VG) CPU at 168MHz clock frequency.

Table 1 describes the result of the profiling. For each variant, we analyzed the runtime latency of each of the three main functions and all of their sub-functions that resides within them. For en/decapsulation, `poly_`R_q`_mul`, `poly_`S_3`_mul` and `poly_`S_q`_mul` accounts for between 85–99% of the total runtime. Accordingly, the aforementioned existing NTRU-KEM accelerators that only accelerated these two functions [2,10,15] aimed to boost the performance of polynomial multiplication. However, in the case of `KEYGEN`, another sub-function, `poly_`R_q`_inv` and `poly_`S_3`_inv`, accounts for the biggest portion over 90%, while `poly_`R_q`_mul` only accounts for 10%. Therefore, in order to accelerate the entire NTRU-KEM algorithm, `poly_`R_q`_inv` and `poly_`S_3`_inv` also needs to be taken into consideration when designing the hardware. It is worth to noting that all the `poly_*_inv` and `poly_*_mul` sub-functions inherently involve parallelism since the computation of each term in the resulting polynomial can be done independently of the others. In addition, `crypto_sort_int32` in encapsulation and `KEYGEN` is also

selected to implement in hardware since it can be processed in a parallel manner. Conversely, the sub-function named `randombytes` within encapsulation and `KEYGEN` function is predominantly comprised of sequential operations. Also, due to its relatively minor contribution to the overall execution time, it has not been implemented as hardware. To efficiently process the above selected two kinds of polynomial operations, the optimizations that we have devised will be presented in the following subsection.

3.2 FSM Oriented Hardware Design

As implied by its name, `poly_`R_q`_mul` includes multiplications between polynomials. The efficient computation of polynomial multiplications is achieved by employing the widely used Fast Fourier Transform (FFT) or Number Theoretic Transform (NTT) technique. These techniques are used in most cryptosystems based on polynomial rings and their hardware implementations [5,6,13,14,16,21]. However, NTRU does not use such operations for two reasons.

Firstly, the rings used in NTRU exhibit properties that are not directly supportive of FFT/NTT. The famous techniques to compute FFT/NTT [3,4] demand that the polynomials be of degrees that are a power of 2. However, NTRU variants are made up of polynomials of degrees that are prime numbers, denoted by n, thereby deviating from the power of two forms. In previous research [7], the polynomial was extended to enable the computation of FFT/NTT, albeit with an increase in the number of operations required by the technique. Secondly, the multiplication of polynomials in NTRU employs a predefined modulo of 3 and q, which can be efficiently computed using a sequence of operations. For instance, a polynomial with modulo 3 assumes values of only -1, 0, and 1 as coefficients. The computation between those coefficients can be processed via such as zeronization and change of sign bit rather than multiplication, which does not incur significant overhead as compared to operations between larger integers.

Based on our observation, we do not employ FFT/NTT technique to multiply NTRU polynomials. However, one drawback of FTT/NTT-less polynomial multiplications is the increase of conditional branches within the algorithm. Especially, the algorithmic structure of `poly_inv` includes a notable presence of conditional branches. This is attributed to the nature of finding an inverse polynomial, which entails a search for the correct match from a pool of candidates, necessitating multiple invoking of `swap` sub-functions.

In order to efficiently handle these conditional branches, our hardware implementation of NTRU leverages Finite State Machines (FSMs) for the computation of sub-functions. FSMs dedicated to each sub-function manage a pool of basic arithmetic units (i.e., multipliers and adders) to process internal operations as much as possible in parallel. The number of basic arithmetic units is carefully determined by our cycle-by-cycle analysis of a group of internal operations within sub-functions. The group of internal operations is based on the conditional branches within the sub-function, resulting in a more fine-grained

Table 2. Parameter Sets of NTRU-KEM

Parameter	NTRU Variant			
	HPS2048509	HPS2048677	HPS4096821	HRSS701
N	509	677	821	701
q	2048	2048	4096	8192

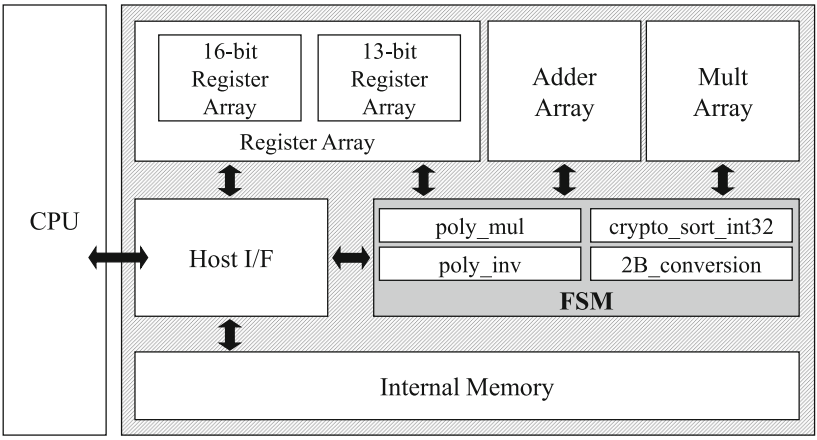

Fig. 2. Overview of Our Hardware Implementation

analysis. In cases where the inherent parallelism of the internal operations is less than the number of available units, all the needed arithmetic units are allocated to maximize parallel processing. Otherwise, although the sub-function cannot be processed as a full parallel, all the units in the pool are pipelined so that multiple operations can be processed in each cycle, thereby minimizing latency. Our FSM-oriented design has enabled us to achieve a balance between performance and hardware area, resulting in an efficient implementation.

4 Implementation

In this section, our implementation details of NTRU acceleration are described. Figure 2 overviews our hardware implementation. We use 16 instances for multipliers and adders with 13-bit and 16-bit integers as both inputs and outputs. In order to optimize the allocation of hardware resources, we decide to employ 13-bit and 16-bit units in a selective manner. The specifics of this implementation approach are explained in the following subsections. The intermediate values are stored in 28 internal registers, allowing for efficient handling of the sub-functions. Additionally, we implement 8 FSMs, with each FSM dedicated to performing one of the 8 sub-functions (`poly_`R_q`_mul`, `poly_`S_3`_mul`, `poly_`S_q`_mul`, `poly_`R_2`_inv_to_`R_q`_inv`, `crypto_sort_int32`, `poly_`R_2`_inv`, `poly_`S_3`_inv`, and `2B_conversion`).

4.1 Supporting All the NTRU Parameter Sets

As shown in Table 2, NTRU has four sets of parameters, each with different polynomial degrees n and modulus prime q. Each parameter set has different security strengths and complexities, so it can be selected and used as needed for various applications. Our implementation entails an accelerator that facilitates the concurrent support of all different parameter sets as a single instance, thereby enabling its versatile utilization for general purposes.

Initially, we determine the bit precision of each intermediate data, including the input and output of arithmetic units and internal registers. Since the prime bit q are different in each parameter set, the number of output bits in modular operations also varies, requiring rearrangement. For the HPS2048509 and HPS2048677 parameters, the q has a valid value in the lower 11 bits (2^{11}). For the HPS4096821 parameters, q has a valid value in 12 bits (2^{12}), and for the HRSS701 parameters, q has the largest valid value of 13 bits (2^{13}). Thus, it has been determined that a bit precision of 13 bits would suffice to represent the polynomial coefficients and its corresponding intermediate outcomes. However, during the execution of the encapsulation process, the sub-function `crypto_sort_int32` necessitates sorting 32-bit data. As this is the only sub-function that demands such a bit precision, we have selectively designed a subset of arithmetic units (2 out of 16 adders) and flexibly grouped a few 16-bit registers (16 out of 28) together to support the processing of 32-bit data, with the purpose of minimizing the hardware resources. Furthermore, it should be noted that `crypto_sort_int32` sub-function is required only in the remaining three of the four parameter sets apart from HRSS701. So, the selective execution of `crypto_sort_int32` is contingent on the parameter set in the HOST I/F module configured by CPU.

Additionally, the `2B_conversion` sub-function also requires 32-bit data input and shares the 16-bit registers used by the `crypto_sort_int32` sub-function. The `2B_conversion` sub-function converts and packs 32-bit data into 1–2 bit data in the R_2 or S_3 ring domain.

4.2 `poly_*_mul` and `poly_*_inv` Sub-Functions

In this subsection and §4.3, the implement details of sub-functions to be accelerated in hardware are explained. As listed up in Table 1, there are four different sub-functions associated with `poly` as a prefix in NTRU: `poly_`R_q`_mul`, `poly_`S_3`_mul`, `poly_`S_q`_mul`, and `poly_`R_2`_inv_to_`R_q`_inv`.

As represented by the notation inserted middle of the sub-function name, each is defined on the different ring domains. In principle, it is ideal for implementing different sub-functions as separate hardware modules since each represents distinct operations. However, upon analyzing low-level sub-operations, it can be found that polynomial multiplication is commonly invoked. In each sub-function, after polynomial multiplication, each newly computed coefficient of polynomials is converted to be compatible with the defined ring domain through modulo operation. The polynomial inverse sub-function additionally involves

Algorithm 1: Polynomial Ring Domain Conversion

Input: polynomial p; inverse polynomial p_inv
Output: Converted polynomial p';

```
Function poly_Rq-to-poly_S3(p):
    for i = 0 to n − 1 do
        if p[i] ≤ 1/2 then
            p[i] =MOD3(p'[i] + 2 ∗ p[n − 1] − 1);
        else
            p[i] =MOD3(p'[i] + 2 ∗ p[n − 1]);
    return p'

Function poly_Rq-to-poly_Sq(p):
    for i = 0 to n − 1 do
        p'[i] =MODQ(p[i] − p[n − 1]);
    return p'

Function poly_R2_inv-to-poly_Rq_inv(p,p_inv):
    for i = 0 to n − 1 do
        b[i] =MODQ(q − p[i]);
    for i = 0 to 1 do
        c = poly_Rq_mul(b, p_inv);
        c[0] = c[0] + 2;
        p_inv = poly_Rq_mul(c, p_inv);
    p' = p_inv;
    return p'
```

comparison and swapping operations. In light of these observations, we implement a common single module to perform polynomial multiplication for use in several sub-functions. Subsequently, the necessary ring domain conversions or remaining operations are carried out in the FSM performing each sub-function to complete the sub-function operation. This approach is feasible since only one of these sub-functions is executed at a time while encapsulation, decapsulation and `KEYGEN` function of NTRU-KEM are performed. As a result, `poly_*_mul`, `poly_*_inv` sub-functions are implemented using hardware resources efficiently.

To elaborate on the implementation detail, multiplication on the R_q ring domain, denoted as R_q`_mul` was selected as the common polynomial multiplication. This is because converting R_q to multiple required ring domains or vice versa was the most efficient. The ring domain conversion carried out within each FSM of `poly_*` sub-function is depicted in Algorithm 1. Algorithm 1 shows the three conversion processes that occur after R_q`_mul`. To convert from R_q domain to S_3 domain, we first need to convert the data with the range from $[0, q-1)$ to $[-q/2, q/2]$. We determine the criterion for performing modulus by checking if the polynomial coefficient is greater than $q/2$, and then perform `modulo` 3 operation to convert the data range to $[0, 2]$. To convert from R_q to S_q domain,

Algorithm 2: Almost-Inverse Algorithm (AIA) [19]

Input: polynomial $A(X)$, $M(X)$, where $A(X)$ is odd and coprime to $M(X)$;
Output: *almost-inverse* of $A(X)$ modulo $M(X)$;degree k

```
1  Initialize F = A(X), B = 1, C = 0, G = M(X), k = 0
2  while true do
3      while F is even do
4          F /= X;
5          C *= X;
6          k++;
7      if F == 1 then
8          return B, k // B is an almost-inverse of A(X) modulo M(X)
9      if deg(F) < deg(G) then
10         swap(F, G);
11         swap(B, C);
12     F += G;
13     B += C;
```

we subtract the polynomial coefficient of the highest degree and perform `modulo` q operation. To convert R_2`_inv` polynomial to R_q`_inv` polynomial, we need to convert data with the range of $[0, 1]$ to $[0, q-1)$. This process involves subtracting the R_2 domain polynomial from q and performing `modulo` q operation, and adding 2 a to polynomial coefficient of the lowest degree after R_q`_mul` sub-function. Using these conversion processes, we can efficiently reuse the R_q`_mul` sub-function in four sub-functions.

As mentioned earlier, the polynomial inverse sub-function involves many conditional statements and swap operations as well as polynomial multiplication. As described in Algorithm 2, NTRU adopts the almost inverse algorithm for efficiency, computing the almost inverse of a polynomial satisfying exact inverse result in all NTRU functions. The inverse process involves iterating through a swap operation, the highest degree with a non-zero coefficient in each polynomial. In NTRU key generation function, there are three required inverse sub-functions: R_2`_inv`, S_3`_inv`, and R_q`_inv`. As can be seen in Algorithm 1, R_q`_inv` can be performed through conversion from R_2`_inv`. So, we only need to implement two sub-functions, R_2`_inv` and S_3`_inv` to evaluate polynomial inverse sub-functions. We found that these two sub-functions exhibit almost the same data flow except for the type of internal computations. Thus, we implemented these two sub-functions into one `poly_inv` sub-function. This unified sub-function is configured by FSMs to operate differently for each case. When `poly_inv` is configured to operate as R_2`_inv`, bitwise OR operations for data with the range of $[0, 1]$ are executed. When `poly_inv` is configured to operate as S_3`_inv`, `modulo` 3 operations for data with the range of $[0, 2]$ are executed. Despite such differences in operations, sub-functions share a common data flow, and they could be effectively integrated into one module.

Table 3. Area of Our Implemented Hardware

	Area ($10^3\mu m^2$)	Percentage (%)
NTRU-KEM	**29.82**	**100**
REGISTER & INTERFACE	4.43	14.90
host I/F	1.37	4.60
register_array	2.65	8.90
mem I/F	0.41	1.40
FSMs	18.94	63.40
poly_mul	8.53	28.50
poly_inv	7.46	25.00
crypto_sort_int32	2.31	7.80
2B_conversion	0.64	2.10
ARITHMETIC UNITS	6.05	20.40
adder_array	1.51	5.10
mult_array	4.54	15.30

4.3 `crypto_sort_int32` Sub-Function

The sub-function `crypto_sort_int32` performs an operation that sorts the sampling data generated with random numbers at the beginning of the encapsulation function in ascending order. The operation is performed on $(n-1)$ data points. In contrast to other polynomial sub-functions, `crypto_sort_int32` sub-function operates on input and output data in units of 16-bit. It is worth mentioning that this sub-function is only required for three of the four NTRU parameter sets. Although the HRSS701 parameter set does not necessitate the execution of `crypto_sort_int32`, it is still imperative to accelerate the function. The rationale behind the acceleration of the `crypto_sort_int32` sub-function lies in its non-negligible contribution to the overall runtime during the encapsulation of the other three sets of parameters. Specifically, this sub-function accounts for approximately 7.6% of the total runtime, thereby emphasizing its significance in the encapsulation process. So, we schedule two *add* units in parallel. This enables the simultaneous comparison of two sampling data points using 16-bit precision. Notably, this approach is compatible with our memory bus width, which is set at 64-bit. By doing so, we can ensure that the processing of the bus data is completed within a single cycle, thereby improving the overall efficiency of the system.

5 Evaluation

To evaluate our design, we targeted our implementation to ASIC using the 45 nm process technology with 1 GHz of clock frequency. We implemented all components of our hardware in verilog-HDL, and synthesized those to the gatelist by

Design Compiler 2017.09-SP2 tool. The rest of the sub-functions that are not implemented in hardware are computed as software by a host processor, Cortex M4(STM32F407VG) CPU at 168MHz of clock frequency.

Table 4. Performance Comparisons with Pure Software in Various Parameters

	Parameters	Latency (ms)		
		KeyGen	Encap	Decap
Software-only [8]	HPS2048509	3489.32	92.10	233.21
	HPS2048677	6094.56	157.91	418.95
	HPS4096821	9164.47	211.15	603.89
	HRSS701	6702.06	160.61	452.73
Ours	HPS2048509	4.02	3.68	1.03
	HPS2048677	4.46	4.39	1.26
	HPS4096821	5.24	4.86	1.59
	HRSS701	4.20	3.55	1.52

5.1 Synthesized Area Result

Table 3 describes the area consumption of our hardware implementation. Out of the overall 29,821μm^2 area used, FSMs accounts for 63.4% while the registers accounts for 8.9%. In the FSM modules, the `poly_mul` sub-function occupied the largest area with 28.50%, followed by the `poly_inv` sub-function, which accounted for 25.00% of the area. These two sub-functions integrate the `poly_*_mul` and `poly_*_inv` sub-functions, respectively, and are designed to allow for the execution of multiple sub-functions as an option. The multiplication and addition arrays, each consisting of 16 elements, are composed of arithmetic units and occupy approximately 20% of the area. Lastly, the `crypto_sort_int32` sub-function was reported to occupy 7.8%.

5.2 Speedup Compared to Pure Software Implementation

In the first two rows of Table 4, we compare the performance of three NTRU functions between ours and the software-baseline in which all the functions are processed on the host CPU. As our software-baseline, we use the official version of NTRU-KEM code submitted in NIST [8]. As reported in the table, `KEYGEN` is the most time-consuming function. This can be attributed to the considerable amount of swapping and condition checking operations required by `KEYGEN`, which are significantly accelerated by our bit-wise FSM controls as well as a pool of arithmetic units. `KEYGEN` function showed an average improvement of 1,393× over four parameters. In an encapsulation function, ours exhibited an average performance improvement of 37× compared to the software implementation.

However, in our implementation, it is noteworthy that about 3% of the operations remained dependent on software, which led to a relatively lower degree of acceleration by hardware. On the other hand, the decapsulation function showed a significant average performance improvement of 307× over the software implementation. Notably, all functions demonstrated the most substantial performance improvements in the parameter set HPS4096821.

Table 5. Performance and Area Comparisons with Hardware in Various Parameters

	Parameters	Latency(ms)		Area	Time*Area	
		Encap	Decap	($10^3\mu m^2$)		
Ours	HPS2048509	3.6868	1.0378	29.82	140.8900	-
	HPS2048677	4.3999	1.2636		168.8845	-
	HPS4096821	4.8623	1.5964		192.5971	-
	HRSS701	3.5529	1.5265		151.4682	-
x-net [2]	HPS2048509	0.0062	0.0071	460.25	6.1213	0.04×
	HPS2048677	0.0084	0.0094	580.47	10.3324	0.06×
	HPS4096821	0.0102	0.0115	728.85	15.8161	0.08×
	HRSS701	0.0041	0.0117	762.17	12.0423	0.08×
comba [2]	HPS2048509	0.3492	1.0471	102.97	143.7770	1.02×
	HPS2048677	0.6161	1.8476	101.04	245.6141	1.45×
	HPS4096821	0.9047	2.7135	99.99	361.7838	1.88×
	HRSS701	0.6604	1.9834	104.69	276.7794	1.83×

† $Time * Area = (Encap\ time + Decap\ time) * Area$

5.3 Performance and Area Comparison with Prior Work

The prior work [2] presents a dedicated hardware design for NTRU encapsulation and decapsulation. They do not provide a single accelerator instance to support all NTRU parameters, thus mandating the need for separate accelerator implementations catering to different parameters. Moreover, the `KEYGEN` process is not implemented in hardware, necessitating a substantial amount of software-hardware communication to deliver the key to the hardware module, particularly when the key undergoes frequent updates throughout the session. Our proposed design, which incorporates `KEYGEN` process in hardware, offers significant acceleration of `KEYGEN`, while simultaneously eliminating unnecessary communication overhead. Along with `KEYGEN`, we have accelerated all three functions involved in NTRU and facilitated acceleration for all parameters with a single accelerator design.

The prior work [2] provides two versions. The first version comba is a design focused on compactness in a similar vein as the goal pursued in our efficient implementation. The other version, x-net is an accelerator designed to focus

on performance, regardless of chip size. The second version significantly maximizes the parallelisms within NTRU functions by instantiating multiple hardware instances. As a result, the second version necessitates an allocation of up to 7 times larger amount of hardware resources as compared to the first version.

For fairness in comparison, we mainly compared the performance and area of our design with the prior work of version comba. It is important to highlight that while x-net may surpass all other implementations in terms of the time*area metric, its area considerably exceeds that of our proposed design by two orders of magnitude. Thus, it is evident that our design is a more efficient and practical solution compared to x-net in terms of area utilization. As compared in Table 5, ours show 1.5 times higher efficiency on average in terms of performance per area, regarding the two function execution times, encapsulation and decapsulation implemented by the prior work. The version x-net is listed together just for reference. It is noteworthy that our design incorporates an additional KEYGEN function and enables support for all parameter sets, which is not a feature present in the prior research. Even when compared to parameters with high complexity, such as HPS4096821, our proposed design employs more than three times less hardware resources, while also exhibiting up to 1.7 times faster performance than the prior work.

6 Conclusion

In this paper, we implement an efficient NTRU-KEM acceleration with full functionality based on a hardware and software co-design methodology. The approach is proven effective in addressing the challenges encountered in implementing the NTRU-KEM, including the significant performance overheads associated with conventional software-based KEYGEN implementation. After the identification of commonly executed operations within sub-functions, we proceeded to develop shareable arithmetic units that could execute sub-functions in parallel. FSMs that are specifically allocated to each sub-function are responsible for managing the processing of sub-functions as an optimal schedule. This scheduling mechanism ensures a balance between performance and hardware resource utilization. The implementation demonstrated a remarkable performance improvement over software-only implementation, as evidenced by a factor of 579× faster. This finding underscores the significant practical value of the approach, especially in situations where frequent key generation is required. Compared to prior work, the implementation stands out as more efficient in terms of hardware resources, offering a performance per area that is exceeds the prior one by up to a factor of 1.8 to the maximum.

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PrinterLeak: Leaking Sensitive Data by Exploiting Printer Display Panels

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Abstract. Sensitive networks hold and process confidential information and, therefore, are kept separate from the Internet. This defensive measure is known as an 'air gap.'

In this paper, we show that attackers can exploit networked printers to exfiltrate data from air-gapped networks. We show that malware in the network can control the printer display screen and status LEDs and modulate sensitive information over them using documented and undocumented firmware and software level commands. Local or remote adversaries can intercept and decode these signals from a few meters to hundreds of meters away. For reception, they can use a smartphone, a local surveillance camera, or camera mounted on a drone. The display panels of printers are currently not monitored or protected by any security measures, such as intrusion detection systems (IDS) and intrusion prevention systems (IPS), which makes this attack highly evasive. We provide technical details, discuss the attack model, and present related work. We evaluate this new type of attack and discuss the necessary countermeasures, both defensive and preventive.

Keywords: air-gap · networks · exfiltration · covert channel · optical · printer · LCD display

1 Introduction

Organizations protect their IT networks with many tiers of defensive measures. Among these are firewalls, security appliances, and intrusion prevention systems at the network level, as well as antivirus software, anti-exploitation, and storage encryption at the host level. However, regardless of the level of security used, local networks are exposed to a wide range of cyber threats from the Internet. When sensitive or confidential information is maintained, the organization may keep the network in a physical 'air gap.' With this setup, the local network is isolated, with no direct connection between the intranet and the Internet. The air-gap policy may be used in defense and military systems, infrastructures,

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public sectors, businesses, and other industries [2]. An example of an air-gapped network is the Joint Worldwide Intelligence Communications System (JWICS), a classified network operated by the US Defense Intelligence Agency.

1.1 Air-Gap Infection

Although air-gapped networks are considered safer, it has been shown that they are not entirely immune to breaches. ESET researchers found more than 20 malicious frameworks appear to target air-gapped networks [8]. In the past, several air-gap breach incidents involve compromising air-gapped networks. In the case of Agent.btz, a classified network of the United States military was infected with an APT worm [1]. Other air-gap hacking cases reported in the past include Stuxnet [25], USBFerry [3], and ProjectSauron [8].

To breach the air-gap isolation, attackers may use sophisticated techniques, such as supply chain attacks, software contamination (E.g., SolarWinds supply chain attack [31]), and insider personnel. With these methods, attackers can evade prevention and detection systems and gain their foothold in the network.

1.2 Air-Gap Exfiltration

Although breaching air-gapped networks has been demonstrated to be feasible, the exfiltration of information from disconnected networks to the Internet is a more challenging problem. This is because there is no network connectivity, wired or wireless, that the attacker can use to leak data outwards. The research domain of special covert communication techniques that work from isolated, air-gapped networks is known as air-gapped covert channels. By employing these techniques, the attacker can modulate information and transfer it. The use of electromagnetic mediums to leak data has been studied for many years. In this approach, malicious code uses electromagnetic leakage from laptops, PC, and servers for data exfiltration. Other techniques include the use of acoustic waves, magnetic fields, thermal emissions, and even vibrations for data exfiltration. The optical medium has also been explored in the context of covert communication channels. Different techniques, such as modulating information over the keyboard and hard drive LEDs, brightness levels, [12], and Infrared, were studied over the years.

1.3 Contribution

This paper introduces a novel optical covert channel to exfiltrate sensitive information from air-gapped networks. We use networked printer(s) connected to the local network and exploit their display panel LEDs and LCD panels to exfiltrate data. The main advantage over the existing air-gap exfiltration method is that the covert channel is maintained by an external device that existing security solutions, such as AVs, IDS, and IPS, do not protect. In addition, the attack is highly relevant to modern IT environments since many environments have one

or multiple printers in their local area networks. Figure 1 shows examples of the display panels that can be used for the covert channels presented in this paper on three leading printer OEMs. We show that attackers can exploit and control the printer display panels and modulate or encode textual and binary data over them in various ways. We also show that video receivers (local or remote) with line-of-sight to the device can record the display panels and deliver the leaked information to the attacker for decoding.



Fig. 1. Example of display panels on three commercial OEMs.

We discuss the adversarial attack model in Sect. 2, and examine the display panels' modulation and encoding techniques in Sect. 3. We evaluate the optical covert channel in Sect. 4. We examine the related work in Sect. 5, present countermeasures in Sect. 6, and conclude in Sect. 7.

2 Adversarial Attack Model

Exfiltration is one of the main stages in the cyber kill chain in Advanced Persistent Threat (APT) [29]. At the attack's foremost step, the adversary must compromise the target network.

A highly secured or air-gapped network can be attacked via supply chain attacks, social engineering, or insider attacks. Note that breaches of secured or air-gapped facilities are a type of attack that has been exhibited in recent years in various security breaches and APTs, such as USBCulprit [11], Agent.Btz [1], Stuxnet [25], and Ramsay [5] attacks.

2.1 Network Mapping

At the initial phase of the attack, the malware scans the network for printers to target. It works by sending packets of data to a network and then analyzing the responses received from all hosts and devices on that network. This allows it to build a network map, which can be used to identify hosts, open ports,

and running services. For example, the attacker may use the Nmap ("Network Mapper") tool, which includes a wide range of features and options, including the ability to scan specific hosts or IP ranges, use different scan types (such as TCP, UDP, or ICMP), and specify different output formats for the scan results. In the case of printers, the Nmap command would be `nmap -p 9100 --open -sV <network>`. This command scans the network for open port 9100, which is commonly used by printers for printing over TCP/IP.

2.2 Data Exfiltration

After breaching the air-gapped network and mapping the printers, the APT collects data from the compromised network and its storage. The data can be textual or binary (e.g., encryption keys and biometric information). For the exfiltration, the APT scans the network and identifies printers in the LAN. Textual or binary information is encoded on the display panels, stealthily and covertly, using various exploitation techniques detailed in Sect. 3.

2.3 Data Reception

The attacker receives optical signals via cameras with a line of sight to the compromised printers. Several types of equipment can be used in this attack model. It includes video surveillance, closed-circuit television, IP cameras, or hidden cameras that have a line of sight to the transmitting device. In this threat model, attackers can also use a malicious insider carrying a recording device (e.g., smartphone) that can position themselves to have a line of sight with the transmitting device. These video cameras record the display panels of network printers. The attacker then decodes the signals and retrieves the encoded data. The list of potential receivers and the corresponding attack vectors is presented in Table 1.

Table 1. The list of potential receivers and the corresponding attack vectors

Receiver	Attack vector
Security cameras	Remote exploitation; Wi-Fi
Hidden local cameras	Supply chain attacks; malicious insiders
Drone-carried cameras	Outsider attack
Recording cameras; smartphones	Malicious insiders/employees/visitors

Figure 2 shows the adversarial attack model. An APT collects sensitive information and encodes it on the printer display panel. The data is recorded by different cameras and transmitted to the attacker across the Internet.

3 Data Transmission and Reception

This section provides information regarding LCD control panels in the context of the covert optical channel and the corresponding attack vectors. It also discusses



Fig. 2. Adversarial attack model. An APT collects sensitive information and encodes it on the printer display panel. The data is recorded by different cameras and transmitted to the attacker across the Internet.

various data modulation and information encoding techniques. Note that the general topic of optical communication, such as screen to camera and LED to the camera, has been widely studied in the context of communication. The relevant papers discuss the types of receivers, bandwidth boundaries, as well as distances [23]. This paper limits the discussion to printer display panels and their relevance to the adversarial attack model.

3.1 Control and Display Panels

Modern printers are equipped with control panels. A typical panel contains buttons, LEDs, and a display screen, also known as a display panel. These panels help to maintain the printer and display printing preferences. The most common buttons are the 'Power,' 'Home,' 'Wireless,' 'Home,' and 'Back' buttons, usually having a corresponding LED.

The display screen of printers is shipped in various types and sizes. The LCD module is an embedded LCD screen, usually a Thin-film-transistor liquid-crystal display module. The older printers have a monochrome passive color display, while the modern printers are commonly shipped with a larger colored LCD screen with larger sizes, e.g., 4.3", 5.7", 7", and 10.1". The display modules are hosted (integrated) in the printer as a system-on-chip and managed by an embedded controller.

In the context of this work, there are three techniques to maintain optical covert channels via the control and display panels (Fig. 3).

- **LEDs modulation.** In this technique, the control panel LEDs are used for data modulation. The behavior of the LEDs and their colors may differ from system to system.
- **LCD screen content.** In this technique, the display screen is used for data exfiltration. The data can be exfiltration directly via the context presented on the screen (e.g., via text or QR code). Another option is to use other data modulation techniques, such as frequency shift keying (FSK), via objects projected on the screen.



Fig. 3. The three techniques to maintain optical covert channels via the control and display panels.

– **LCD screen brightness.** In this technique, the control screen is used for data exfiltration. However, the screen's content is not modified; only the background color is used to modulate and encode the information.

Table 2 Summarized the three techniques for the optical covert channel. LED modulation is available in all printers and is highly stealthy. The LCD screen content modulation is relevant to all modern printers but is less stealthy since the user may notice the screen content changes. In such a scenario, the attacker is usually absent during an overnight attack. In today's printers, LCD screen brightness is available, so the user may not notice any changes to the screen content if the brightness is close enough. Note that previous work showed that close brightness levels are considered covert in terms of user awareness but can be detected with standard video cameras [12].

Table 2. The three techniques of the optical covert channel from the printer control panel

#	Method	Modulation	Stealth	Availability
1	LEDs modulation	Blinking frequency	High	All printers
2	LCD screen content	Content information	Low	All modern printers
3	LCD screen brightness	Brightness modulation	High	All modern printers

3.2 Attacking the Printer

We present three methods malware can use to infiltrate the printer control/display panel.

Firmware Attack. The attacker updates the printer firmware with malicious firmware that controls the panel and buttons' LEDs and the display screen content. Within the firmware, changing the LED state requires access to low-level registers or GPIOs, depending on the specific system. After compromising the firmware with the screen and LED control, the attacker can maintain C&C with

the printer via standard protocols such as HTTP requests, Telnet, SMB, etc. Note that this method enables the highest degree of control over display panels but is hardware-specific and mostly undocumented. As shown in previous work, many printers are vulnerable to firmware attacks. Many printer OEMs use print job mechanisms for firmware updates. Firmware modification attacks against network printers have been demonstrated by Stolfo et al. for HP printers [7], by Jordan for Canon printers, and by Weidenbach and Ernst for Xerox printers [4].

Remote Configuration Attack. In this method, no firmware modification is required. Instead, the attacker uses documented and undocumented *configuration* commands to modify the LEDs and screen content. In many network printers, the Printer Job Language (PJL), originally developed by Hewlett-Packard, can be used to modify the screen content on the fly. The PJL can control jobs, perform language switching, job separation, status readback, and issue file system commands. For example, the PJL command `[%-12345X@PJL RDYMSG DISPLAY= "SECRET PASSWORD" [%-12345X` cause the current display message to be changed to the `SECRET PASSWORD`. In addition, in modern printers, various configuration commands can also be delivered via standard HTTP requests processed by the printer's internal HTTP server. The configuration attack that can be used in this method includes modifying the display panel content, setting icons, and changing the date and time, status icons, text messages, etc. Figure 4 shows the remote configuration attack viewed by the Wireshark network protocol analyzer. In this case, the malware used the Printer Job Language command to exfiltrate a secret password by displaying it on the printer screen for a limited time.

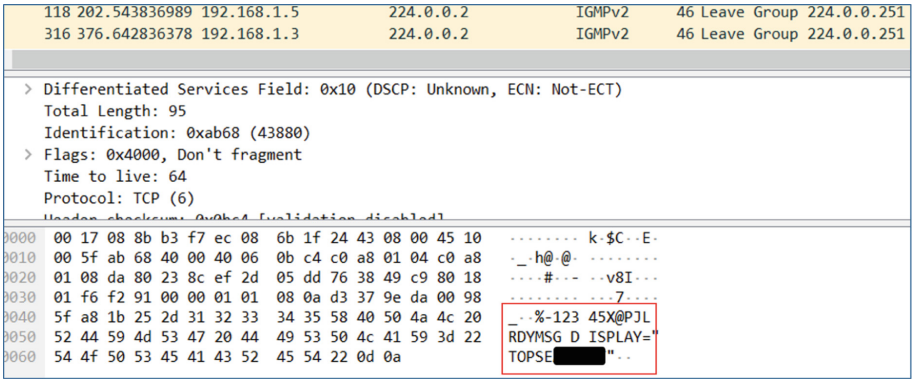

Fig. 4. Remote configuration attack as viewed by the Wireshark network protocol analyzer. In this case the malware used Printer Job Language (PJL) undocumented command to exfiltrate a secret password in the printer display screen.

Remote Operation Attack. In this method, the attackers used *control* commands to modify the LEDs and screen content. This is done via known protocols such as Printer Control Language (PCL), Printer Job Language (PJL), Internet Printing Protocol (IPP), SMB, and others. Communication is done via HTTP commands or dedicated ports such as 9100 (AppSocket), 515 (Line Printer Daemon), and 631 (Internet Printing Protocol). The commands can include setting job names, adding printing jobs to the queue and cancelling it. They can also include setting warning messages, resetting the printer, setting queue status, etc.

Table 3 presents the three attack methods, their relevance, and the corresponding attack vectors.

Table 3. The three attack methods, their relevancy to LED and LCD attack, and the corresponding attack vectors

#	Technique	LEDs	LCD	Attack vectors
1	Firmware attack	Yes	Yes	Firmware updates, local or via FTP, Telnet, and HTTPS
2	Remote configuration attack	Partial	Yes	Printer Command Language (PCL), Printer Job Language (PJL), printer HTTPS POST command
3	Printer commands attack	Partial	Yes	Spooler commands, Printer Command Language (PCL), Printer Job Language (PJL), printer POST commands

3.3 Data Modulation and Encoding

Using the signal generation techniques described above, we implemented three different types of data modulation; (1) frequency shift keying (FSK), (2) content modulation, and (3) brightness modulation.

Frequency Shift Keying (FSK). This modulation can be used for both LED control and screen control. The lack of a signal for a specific time duration encodes a zero (‘0’), while its presence for a time duration encodes a one (‘1’). In our case, the LED blinks at specific frequencies to encode ‘1’ and ‘0’. Note the generally modulating information over LED control is discussed in [18,26,27]. The FSK can also be used to modulate information over the LCD screen. In this case, a visual symbol (e.g., a black rectangle) modulates the binary information with the FSK.

Content Modulation. This encoding uses the LCD screen to exfiltration the information. The textual and binary information can be encoded in plain text, such as showing the text or image on the screen for a certain time. Another method is to use more complex encoding schemes, such as QR codes, which can be used to transfer binary and encrypted information. Modulating information over visual content is discussed in [13,30].

Brightness Modulation. The brightness modulation scheme uses different brightness levels to modulate the information. This can be seen as a form of frequency modulation at the carrier level since different colors have different

wavelengths from the optical perspective. In most simple cases, the current background encodes '0', and the darker or brighter background encodes '1'. We separate two sequential bits by setting the background to the current level for time interval T_d. Modulating information over screen brightness is discussed in [12].

4 Evaluation and Analysis

In this section, we evaluate the optical covert channel. We assume a line of sight between the printer and the recording camera (e.g., a surveillance camera or a smartphone).

4.1 Effective Distance

The number of camera frames per second (FPS) is one of the main factors important for successful reception. Three frames per bit is an optimal setting to decode the LED or LCD modulations. It means that even devices with relatively low frame rates, such as security cameras, can be used for data recording. Table 4 shows the effective distances with different types of receivers. We include a surveillance camera, a DSLR camera, a high-resolution camera, a webcam, a smartphone camera, and a telescope camera. It is known that telescopes and special focus lenses can extend the range of reception to hundred meters [23].

Table 4. The effective distance with different receivers

Receiver	Type	Distance
Surveillance camera	Sony SNCEB 30fps	30 m
DSLR camera	Nikon	50 m
high resolution camera	GoPro	50 m
Webcam	Microsoft LifeCam	30 m
Smartphone camera	Samsung Galaxy	30 m
Telescope	Various	100 m

4.2 Data Transmission

Table 5 show the time it takes to exfiltrate various types of information with each method. Note that the exact time may change from printer to printer depending on the display panel type and size. A 128 bits password (16 bytes) can be exfiltrated in less than a minute or real-time, depending on the exfiltration method. Bitcoin private key and pin codes can be exfiltrated in less than a minute with all methods. An RSA encryption key of 4096 bits takes between 5 min to 30 min, depending on the method used. For keystrokes, each keystroke can be leaked in almost real-time. Small images and QR codes are relevant only for LCD screen content modulation and can be exfiltrated in real time.

Table 5. The exfiltration of various types of information with each method

]Information	Size	Display Panel LEDs	LCD screen content	LCD screen brightness
Passwords	128 bits	0.5 min	realtime	1 min
Bitcoin private key	256 bits	1 min	realtime	2 min
PIN codes	64 bits	0.25 min	realtime	0.5 min
RSA encryption keys	4096 bits	20 min	5 min	30 min
Keylogging	8 bits per key	realtime	realtime	realtime
Small image	64×64	N/A	realtime	N/A
QR code	21×21	N/A	realtime	N/A

4.3 Visual Detection

With the cameras specified in Table 4, we achieved about 100% detection rates of the panel LEDs, which maintained 20 bps per LED. The cameras were able to accurately detect the LED's in various lighting conditions and at a wide range of distances. The results were reliable, consistent and showed no signs of deterioration over time. As a result, these cameras provide a dependable and accurate solution to detecting panel LEDs. This is regardless of lighting conditions or distance in our attack model. Our algorithm performs the following steps for each video frame.

1. Convert the image to grayscale.
2. Apply a Gaussian blur to reduce noise in the image.
3. Apply a threshold to the image to create a binary image, where the LED(s) should be brighter than the background.
4. Apply morphological operations (erosion and dilation), to remove small objects and fill gaps in the binary image.
5. Find contours in the binary image.
6. For each contour, calculate its area and centroid.
7. Apply a circularity test to each contour to filter out non-circular shapes that are not likely to be LEDs.
8. Apply color filtering to further isolate the LEDs in the image (if they have a specific color).
9. Marks the detected LEDs using their centroids and radii.

4.4 Distance Analysis

We presented the covert channel distance given specific transmitters and receivers. An optical communication formula can calculate the effective distance in the general case.

$$P_r = P_t \frac{A_r}{d^2} \tag{1}$$

where P_r is the received power, P_t is the transmitted power, A_r is the effective area of the receiver, and d is the distance between the transmitter and receiver.

In this formula, P_r is the power the receiver receives, which is the LED receiving the signal. P_t is the power transmitted by the transmitter, which is the LED sending the signal. The effective area of the receiver A_r is the area of the receiver that can capture the signal. d is the distance between the transmitter and receiver. The formula states that the received power, P_r, is equal to the transmitted power P_t, multiplied by the ratio of the effective area of the receiver A_r, to the square of the distance between the transmitter and receiver d^2. This relationship is known as the inverse square law, which states that radiation intensity decreases as the square of the distance from the source increases. Consequentially, as the distance between the transmitter (the printer display panel) and receiver (the receiving camera) increases, the received power decreases because the signal spreads over a larger area. Similarly, if the receiving camera effective area is larger, more of the optical signals will be captured, and the received power will increase.

Bit Error Rates (BER). There are a number of factors that affect the bit error rate in our covert communication channel, including the threshold voltage, the noise standard deviation, and the signal-to-noise ratio of the received signal. This formula can be expressed as follows.

$$\text{BER} = \frac{1}{2}\text{erfc}\left(\sqrt{\frac{I \cdot h \cdot d}{2qAN_0}}\right) \tag{2}$$

This is a special function that represents the probability that a Gaussian random variable will exceed a given threshold. Using erfc as the complementary error function, the LED current is I, h is the photodetector's sensitivity, d is the distance between the light source, q is the elementary charge, A is the photodetector's area, and N_0 is the noise power spectral density. Note that an in-depth analysis of optical channel characteristics is beyond the scope of this paper and is given in relevant literature on optical communication [32].

5 Related Work

The term covert channel refers to a communication channel that enables data transfer between entities where communication is forbidden. Covert channels are widely studied in the context of covert communication between processes, CPU cores, virtual machines, and computers.

To maintain covert communication while bypassing security measures, attackers may use various legitimate protocols to conceal information, including protocols such as TCP/IP, HTTP, SMTP, and DNS [28].

In the air-gap scenario, covert communication is more challenging since there is no Internet connectivity. An attacker may use out-of-band communication

techniques categorized into electromagnetic, magnetic, acoustic, thermal, and optical channels to exfiltrate data through the air gap. These special types of covert channels are also called air-gap covert channels. Electromagnetic medium is the most common subject of research in this field. The techniques involve using components that emit electromagnetic waves in computers or devices and exploiting them to modulate sensitive information.

Kuhn used radio frequencies emanating from display screens to leak information [24]. Modern attacks such as Air-Fi [9], AirHopper [15], and GSMem [14] use computer buses to modulate information in various frequency bands and deliver it to nearby malware-infected mobile phones. Similarly, magnetic covert channels have recently been proposed to exfiltrate data from air-gapped computers kept in Faraday cages [21]. Bauer et al. discussed using anti-EMI features in the CPU for communication [6]. Research from previous years also demonstrated the use of power lines to carry covert communication [19].

Sound also can be used to maintain covert communication, especially in inaudible frequency bands, mainly above 18 kHz.

Hanspach et al. showed different acoustic frequencies to maintain contact between computers [22]. However, speakers might be forbidden in air-gapped networks in a defense measure known as an 'audio gap.' Guri et al. introduced cover channels for air-gapped, audio-gapped networks in methods such as Fansmitter [17], Diskfiltration, and PowerSupplay [10]. With these techniques, malware can produce sound waves without standard audio hardware. Thermal-based covert channels between computers were also demonstrated. BitWhisper is an attack that exploits heat emission and heat sensors in computers to maintain data transmission overheat [16].

5.1 Optical

Loughry presented the threats of covert communication with optical emanations via network and keyboard row of LEDs [26,27]. Guri et al. introduced the modern adversarial attack model by encoding signals sent from USB keyboard LEDs at various speeds [18]. They also exploited hard disk drives (HDD) status LEDs and network devices LEDs [20]. Two attacks relevant to LCD screens are Brightness [12], and VisiSploit [13], which use LCD display screens to conceal information. With these methods, invisible images or brightness levels are used to encode sensitive information. Remote cameras receive and decode data. Other works proposed to project invisible images on screens to secure air-gapped infrastructures [30]. Note that all previous works used the standard LCD screen of computers and hence can be monitored by AV, IDS, and IPS systems. Networked printer display panels currently lack protection and defense measures.

This work presents the usage of networked printer display panels to retrieve data from air-gapped networks. The network printer display screen used for malicious purposes has not been studied before, theoretically or technically. We examined this covert channel technique's characteristics, opportunities, and limitations. We discuss attack vectors at the firmware to software level, transmission methods, and various receivers.

6 Countermeasures

The main protective countermeasures for optical attacks include the restriction of cameras and video recorders in areas of networked printer devices. However, surveillance cameras cannot be banned since, in many cases, they monitor sensitive areas. Host-based filtering is another way of mitigating the optical threat presented in this paper. In this approach, a network filter component is installed on the computer, usually as a driver in the kernel. This driver filters all network traffic at the lowest level before transferring data to the network card. The driver monitors all network protocols - Ethernet, IP, TCP, UDP, and performs deep packet inspection to detect attacks. Figure 5 shows the architecture of such a firewall implementation on Windows OS. The Network Driver Interface Specification (NDIS) filter driver filters printer traffic at different ports (e.g., 9100 and 80), and if an attack is detected, the traffic is blocked. An external firewall is another solution that may be deployed as a detection and prevention system on a local LAN firewall (Fig. 6, A). In this case, a stateful inspection paradigm is used to inspect each printer's traffic separately, identify suspicious traffic, and block it. Such a hardware solution can be deployed as a dedicated hardware firewall where each printer has a small device filtering its LAN incoming traffic (Fig. 6, B). An external monitoring solution includes a local video camera that records the networked printer to detect anomalies in its optical activities at the control panel. A practical implementation of external monitoring would be complex because the printer screen content may be related to a specific vendor. It is challenging to define anomalies in their content. In addition, this type of detection would likely have high rates of false positives due to the legitimate dynamic content on the printer display screen. This is due to warning and error messages, notifications and alerts, etc.



Fig. 5. The architecture of the printer firewall on Windows OS as an NDIS filter driver.

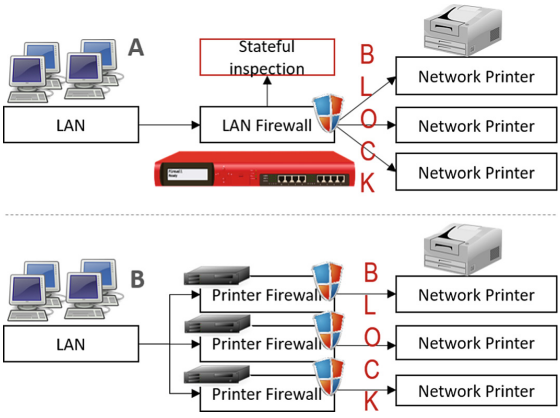

Fig. 6. The two types of firewall architecture used to detect and block the attacks; are (A) a stateful module on the network and (B) a printer firewall device for each networked printer.

7 Conclusion

This paper explores a new type of covert channel that enables attackers to leak data from air-gap networks. Our attack exploits networked printers' display screens and status LEDs to encode sensitive data. To that end, the attack uses documented and undocumented commands at a user process or firmware level. Information such as keystrokes, texts, credentials, passwords, and encryption keys can be encoded and modulated over these signals. These signals can be intercepted and decoded by an adversary with line-of-sight to the printer. For example, using a drone, local surveillance camera, and smartphone camera. We presented related work, discussed the various attack techniques, and proposed hardware and software defensive countermeasures for this attack.

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Design of an Integrated Cyber Defense Platform for Communication Network Security of Intelligent Smart Units

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Abstract. The key to building an intelligent smart unit promoted by military advanced countries is to strengthen security based on new technologies of the 4th Industrial Revolution. It should be manageable the security of information system and network in real time by applying new information and communication technologies such as artificial intelligence and big data. As various new technologies are applied to the information and communication networks of smart units, vulnerabilities will increase, and sophisticated cyber threats using these vulnerabilities will also increase. Artificial intelligence and big data technologies are essential for the integrated security control system of a smart city currently being built. They are also needed for the cyber security orchestration and security control system developed by a company. So, it processes, classifies, and analyzes massive data in real time, detects threats more accurately, and reduces false detection rates. In this study, we proposes an integrated cyber defense platform design that can process data, detect threats, and judge true/false detection in real time based on the functions of the existing integrated security control system and the characteristics of the information communication network of intelligent smart units.

Keywords: Integrated Cyber Defense Platform · Threat Detection · True/False Detection Rate · Intelligent Cyber Attack · Intelligent Smart Unit

1 Introduction

Military advanced countries are converting existing units into intelligent smart units, advanced combat units, so that they can conduct military operations quickly and efficiently by applying new technologies of the 4th Industrial Revolution (IR) [1]. In particular, South Korea is promoting Defense Innovation 4.0 with the aim of fostering an AI science and technology powerful military through advanced science and technology-based military innovation. Its purpose is to equip swift and accurate operation/mission capability and smart organization/system/procedure through intelligence of weapon system, high efficiency of operating environment, and advancement of technology and infrastructure [2]. Currently, new technologies such as artificial intelligence and big data are being applied to advanced weapon systems including military operation systems, base defense systems, and operation support systems in the intelligent smart units. In addition,

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the weapon system to be introduced in the future will be equipped with advanced intelligent software. As the high-tech application system is diversified and advanced, security problems have begun to emerge. Security systems such as firewalls, intrusion prevention system (IPS), network access control (NAC), and antivirus systems for integrated networks and terminals that have been previously installed cannot secure the safety and reliability of various mission systems that are becoming advanced and large-scale.

The aspect of recent cyber threats is utilizing intelligent and sophisticated attack techniques. In particular, as artificial intelligence and big data technology are applied to cyber-attack techniques, it is becoming difficult to identify and detect cyber threats with cyber security systems. Therefore, it is necessary to install an integrated cyber defense platform to comprehensively control the information communication network of intelligent smart unit and respond to intelligent cyber threats [3].

We propose an integrated cyber defense platform design that can protect mission system of Korea's intelligent smart unit, respond to various cyber threats, and manage each security system and information system. We explains the building status of Korea's intelligent smart units in Sect. 2, and describes the security threats of intelligent smart units in Sect. 3. We propose the design of an integrated cyber defense platform in Sect. 4 and conclude in Sect. 5.

2 The Building Status of Intelligent Smart Units in South Korea

In the era of the 4th Industrial Revolution (IR), military advanced countries such as the United States are already converting and promoting military innovation based on advanced science and technology. The Ministry of National Defense of Korea is promoting Defense Innovation 4.0 in order to actively respond to the paradigm shift in defense and warfare following the innovative development of the 4th IR technology. Defense Innovation 4.0 intends to redesign and remodel all areas of national defense such as defense R&D, power reinforcement system, defense science and technology, military strategy and operational concept, and military structure and operation in order to retain and operates core advanced forces based on 4th IR science and technology such as AI, unmanned robots, etc. Finally, it aims to build a powerful AI science and technology force with a competitive advantage. In accordance with Defense Innovation 4.0, each military is building intelligent smart units using new technologies of the 4th IR [2].

The Army is building advanced and strong units that can monitor the current operational status of all units in real time by applying new technologies of the 4th IR, such as artificial intelligence, big data, augmented/virtual reality, 5G, and the Internet of Things (IoT). The Army's smart unit consists of a super-intelligence platform, a super-convergence intelligence information center, and a hyper-connected network. The super-intelligence platform consists of a warrior platform, an intelligent personnel management/military maintenance system, an intelligent LVCG (Live, Virtual, Constructive, and Game) system, an automated unmanned security system, and a smart troop management system. The super-convergence intelligence information center is based on artificial intelligence and consists of an open algorithm, a high-speed processing shooter computing system, and a data platform for learning. The hyper-connected network establishes

an integrated network system by connecting all platforms, and constitutes an Army-only communication network that can visualize the battlefield by connecting communication networks, means of maneuver, means of surveillance and strike in real time. And Army Tiger 4.0(Army Transformative Innovation of Ground forces Enhanced by the 4th IR technology), the Army's future core combat system, is equipped with optimal detection, determination, and strike capabilities with mobility, networking, real-time hyper-connectivity, and super-intelligence technology [4].

The Navy applies the advanced ICT-based technology to ships to integrate the loading system, reflect the automation system, connect advanced manned / unmanned naval platforms with an intelligent network, and reinforce response capability of maritime accidents and disasters in order to build a smart naval combat system. The smart naval system consists of a system-integrated battleship, a maritime unmanned system, and a wide sea area battlefield surveillance system. System-integrated combat ships build an integrated ship computing environment so that various systems can be operated in a single server environment, and apply automation technology to reduce combat response time and increase maintenance efficiency. The maritime unmanned system is the core of manned/unmanned forces along with combat ships, and consists of three types: unmanned surface boats, unmanned submarines, and unmanned aerial vehicles. And the function will be developed from surveillance/reconnaissance to combat. The wide sea area surveillance system is planned to be built as a system that can detect and monitor long-distance maritime and underwater targets by establishing an over-the-horizon (OTH) radar and a fixed/buoy type underwater surveillance system [5].

The Air Force intend to build a smart air force based on the advanced of the 4th IR as building system such as an intelligent command decision system and aerial unmanned system based on big data and artificial intelligence, an unmanned access control system based on AI and the IoT, a base security system using drones/robots, and demand prediction system for aircraft repair parts based on AI and big data, and a remote base environment management system based on the IoT. The Air Force's super-intelligent smart flight wings is consisted of infrastructure, a platform that processes information collected from the infrastructure, and an application system that utilizes data. The standard platform consists of a standard collection/linkage system that integrates and links networks for each operating systems/equipment, a data integration/distribution system that integrates, classifies/summarizes, and searches/converts various application system data, a content linkage system that exchanges various service linkage (API, etc.) and application system data. The application system consists of a unit situation sharing system that monitors/controls all situations within the command center unit, a base boundary monitoring system that performs real-time monitoring & control and manned/unmanned complex alert operations, facility remote monitoring system for real-time remote monitoring and control of equipment/materials (ammunition, oil, etc.) and so on. The intelligent smart flight wings is a new ICT-based high-tech flight wings that integrates individual operating systems and equipment such as computers and CCTVs in the base through a network to control the operation situation of aircraft, facilities, and equipment in a three-dimensional manner anytime, anywhere. The below figure shows the concept of an intelligent flight wing being promoted by the Air Force. The Air Force intends to be intellectualized all systems with functions

such as monitoring/surveillance/prediction/detection/management/training by utilizing the 4th IR technology [6, 7] (Fig. 1).

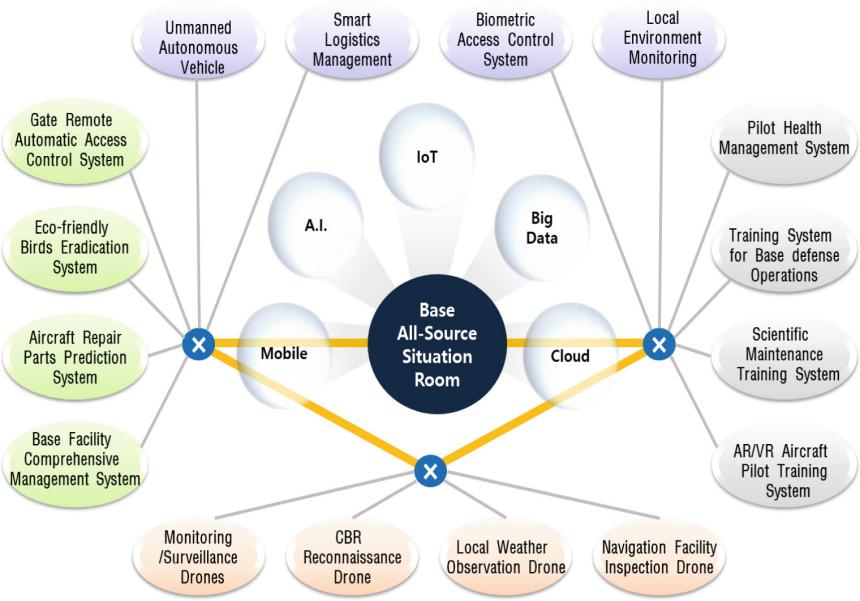

Fig. 1. The concept of an intelligent smart Air Force unit using 4th IR technology

3 Security Threats of Intelligent Smart Units

3.1 Security Vulnerabilities of Intelligent Smart Units

The communication network of the intelligent smart unit is composed of a closed network, so security threats from the outside will be limited. However, if the network is connected to the Air Force headquarters, the Ministry of National Defense, or military organizations connected to the external network, there is a possibility of threat from the outside. The security threats of smart cities, which are similar to the composition and service of intelligent smart units, are classified into outsiders, insiders, and internal/external connection points for security management [8]. Since intelligent smart units operate as a closed network, security threats from an insider's point of view are most likely to occur among security threats in smart cities. In particular, the most serious vulnerabilities are threats arising from internal infrastructure and communication networks. Internal infrastructure threats can occur by exploiting vulnerabilities in the IT infrastructure or by using unauthorized users' internal systems. Threats to the internal communication network may leak internal information through stealing identification and authentication information in the data processing section. An additional security threat is a security threat that can occur in collusion with an insider. Insiders include

employees working in the smart unit, external employees residing within the unit, and external employees who periodically come in and out for system/communication management. If an external employee for checking system/communication connects a PC or USB with ransomware or APT attack programs to the unit's communication network, the most serious damage will occur. Also, supply chain attacks can occur. When a new system is introduced to replace an old system in the unit, a developer or supplier may implant malicious code into the new system for malicious purposes. When a new system infected with malware is installed in the unit, connected to the network and operated, all connected systems are infected.

3.2 Possible Cyber-Attacks Scenarios in Intelligent Smart Units

As mentioned above, since the network of intelligent smart unit is composed of a closed network, a security threat scenario is presented by using cyber-attack techniques with a high possibility of cyber threat targeting the internal network in recent cyber-attack cases. Closed networks have limitations in intruding directly from the outside through the network, so most cases use insider-based attack techniques or supply chain attack [9].

First, it is to use the laptop of an external employee who regularly come in and out the unit for checking system/network (Fig. 2). A hacker injects malware into the laptop

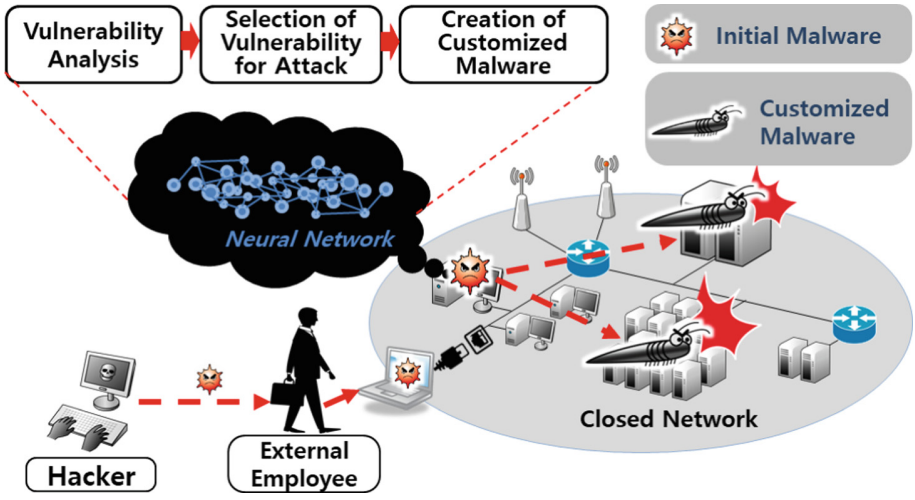

Fig. 2. AI-based malware infection using insiders

of an external employee. And when an external employee connects his laptop to the closed network to check the unit's system and network, the malware code installed in the laptop infects the closed network. Recently, malware perform more intelligent and autonomous functions by applying artificial intelligence. In the past, all processes were programmed by hacker (human), but now, it can be produced quickly and precisely by automating everything from analyzing vulnerabilities to programing malicious codes through artificial intelligence. AI-based malware infects only one system even if it does

not know specific network configuration information inside the closed network, and then uses artificial intelligence to scan surrounding systems and exploits vulnerabilities. After that, it creates a secondary malicious code and infects all systems through self-propagation inside the closed network.

Second, it is a supply chain attack that has recently become a security issue (Fig. 3). Supply chain attacks are mainly used when attacking systems and data that are not easy to attack directly from the outside. When hackers plant malware in the software or systems of software developers and vendors, and when that software or system is installed on the internal network, all connected systems are infected with the malware [10]. Therefore, it is mainly used when attacking systems or data within a closed network that is difficult to intrude from the outside. However, it takes a long time for the software to be developed and installed on the closed network to be attacked. A variety of software or firmware is installed in the closed network of intelligent smart unit, from the infrastructure system to the main asset management & support system and control/command system. In order to always keep them up to date, they are downloaded by connecting to the update server of each software/firmware manufacturer, or an outside company manager directly accesses the base and installs them. Using this point, an attacker can secretly intervene in the software/firmware development process and perform a supply chain attack in order to infect systems inside the closed network with malicious code. The supply chain attack utilizes the following techniques.

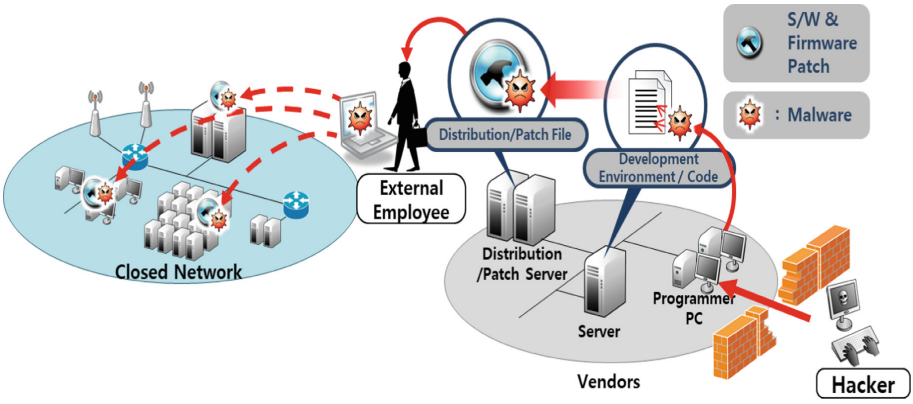

Fig. 3. Penetrating closed networks using supply chain attacks

- A method of infiltrating and tampering with software development (build/update) infrastructure
- A method to sign and distribute certificates of malicious software created by hijacking legitimate certificates used to verify the integrity of software
- A method of infiltrating the internal network by modifying the firmware of network equipment such as switches and routers

4 Design of an Integrated Cyber Defense Platform

The integrated cyber defense platform should include functions to monitor, detect, analyze, and share cyber threats occurring in the mission system such as military operation system, base defense operation system, operation support system, and education and training system. In this chapter, we derive the requirements for designing an integrated cyber defense platform, and propose the design of overall integrated cyber defense platform and the functions of modules.

4.1 Requirements for Designing an Integrated Cyber Defense Platform

As various new technologies are applied to the mission system of intelligent smart units, vulnerabilities will increase, and cyber threats using these vulnerabilities will increase. Recently, the aspect of cyber threats uses intelligent and sophisticated techniques. It is necessary to design an integrated cyber defense platform that can ensure the safety and reliability of the mission system, manage heterogeneous security systems, and monitor/detect/analyze/respond to sophisticated cyber threats in real time. Therefore, it is necessary to derive requirements prior to designing an integrated cyber defense platform.

First, it is necessary to know the type and function of the mission system as well as the applied technology and system configuration operated in the intelligent smart unit. By analyzing the types and functions of the mission system, it is possible to identify a system that performs similar functions in the private sector and to identify the system's vulnerabilities, possible errors or threats. Also, by analyzing the applied technology and configuration status, it is possible to know the vulnerabilities of the applied technology and cyber threats that may occur to the applied technology. In addition, it is necessary to accurately understand the configuration of all network infrastructures to manage networks reliably and to block only those networks when cyber threats occur.

Second, it is necessary to identify the types, performance, and applied technologies of security systems and software installed in closed network and system. It is necessary to analyze whether a security system capable of responding to each type of cyber threat is installed and how well it performs. It is also necessary to check if security functions are duplicated or if a security system capable of responding to threats is not installed. In addition, it is necessary to check whether security functions such as prevention, detection, analysis, sharing, and recovery are missing, and it is necessary to check whether the latest version of the security system is maintained. And it is necessary to check whether new technologies are applied to the security system to respond to sophisticated cyber threats.

Third, it is necessary to be aware of the latest intelligent cyber threats. Among recent cyber threats, intelligent cyber-attacks using convergence tools combining ransomware and APT attack methods and cyber-attack tools with artificial intelligence are difficult to detect with existing security techniques. These cyber threat methods will evolve into more powerful cyber-attack tools through mutual convergence in the future. In addition, artificial intelligence technology will be applied to various cyber-attack tools to achieve more sophisticated and covert attacks. It is necessary to understand the aspects of these intelligent cyber threats in advance so that prevention/detection/analysis functions can be performed accordingly.

Fourth, it is necessary to check linkage between the integrated cyber defense platform and heterogeneous security systems, management methods, and overlapping functions. In other words, it has to determine whether to send only data detected as abnormal behavior in heterogeneous security systems to the integrated cyber defense platform, or send all data except normal behavior data. If all heterogeneous security systems send data to the integrated cyber defense platform, performance degradation and overload problems of the integrated cyber defense platform may occur. In addition, it is necessary to compare whether the functions of the modules of the integrated cyber defense platform overlap with the functions of heterogeneous security systems.

Finally, it should be considered the scalability of the integrated cyber defense platform. An intelligent smart unit can be additionally installed with other mission systems and can be linked with other units. And he future cyber threats that can act as a game changer may occur. As the scope of monitoring cyber assets and threats expands, the platform's functions and modules must also be added.

4.2 Design of an Integrated Cyber Defense Platform

The proposed integrated cyber defense platform was designed by referring to models such as smart city integrated security control system, intelligent integrated security control model, cyber security orchestration, and next-generation security control system. Recently, intelligent/next-generation integrated security control systems utilize artificial intelligence and big data technologies to enable faster data processing, classification, and analysis, more accurately detect threats, and reduce false detection rates [11–13]. The proposed platform also applies big data technology to data collection, processing, classification, and analysis, and applies artificial intelligence technology to analyze and block threats and determine true and false detection.

The integrated cyber defense platform receives security events and suspicious data from heterogeneous security systems installed in the information and communication system of intelligent smart units. And if a threat is detected by analyzing the data, it automatically blocks the threat immediately. In addition, true/false detections are judged once again for the results determined by the individual security system and threat detection module of the platform. If it is judged to be a true positive, it is reported to the base all-source situation room and notified to the incident response team to conduct an accident investigation.

The integrated cyber defense platform consists of seven modules and performs functions such as big data collection and analysis, threat detection and blocking, true/false decision, security system management. The database stores and manages data related to integrated security policies, artificial intelligence and big data (Fig. 4).

The big data collection module collects and processes all security events generated from various heterogeneous security systems based on big data technology. Since various types of events occur in heterogeneous security equipment, various raw data are classified/sorted/refined and classified into structured data and unstructured data. And it interprets and transforms the data so that it can be used in the integrated cyber defense platform. Since raw data is composed according to each language or form, it must be reproduced as meaningful data through data preprocessing techniques.

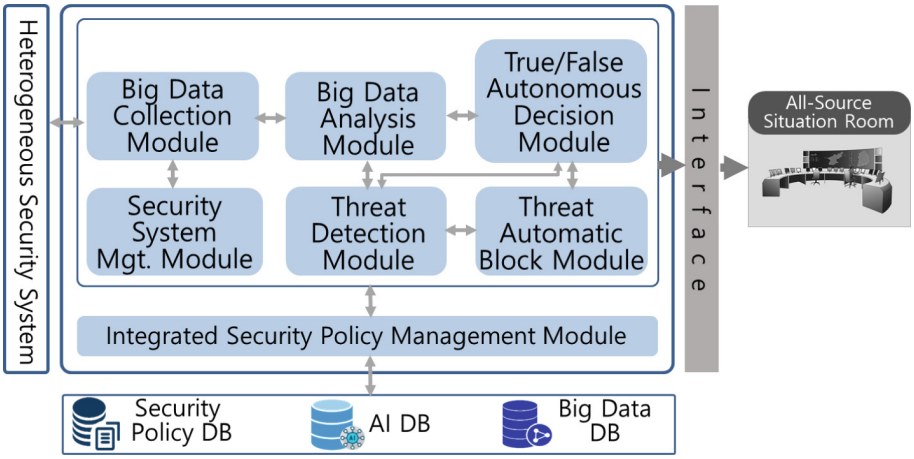

Fig. 4. Design of Integrated Cyber Defense Platform

The big data analysis module performs real-time automatic high-speed search for data related to security threats among data received from the collection module, and performs various big data analysis functions such as threat-related data classification and association (correlation) analysis. In the analysis module, the relationship between threat-related data and between the data set and other data is analyzed in terms of time and causal correlation.

The security system management module manages the operating status of heterogeneous security systems installed to protect various mission systems. When a new or changed security policy is received from the integrated security policy management module, it is sent to the relevant security system so that the security policy can be modified. In addition, the normal operation of heterogeneous security systems is monitored to continuously check for abnormalities. If a problem occurs in the security system, the information is sent to the situation room so that action can be taken.

The threat detection module analyzes the data received from the big data analysis module to determine threats. When judging threats, an algorithm that can quickly and automatically process a large number of security events and an intelligent algorithm that can detect highly complex security events must be applied to reduce false detection rates. Among AI technologies, if supervised/unsupervised learning algorithms are used, large-volume security events and complex security events can be automatically processed and threats can be determined. Since intelligent cyber threats are not one-time, but continuously change the attack type for a long period of time, it is difficult to detect them with a matching algorithm such as a string or pattern (a signature-based algorithm). These intelligent cyber threats must be detected by unsupervised learning algorithm of an AI. AI's unsupervised learning algorithm is a learning model in which AI classifies and judges by itself when various problems are input and derives the result value. In other words, when security events acquired by various security systems are trained with an unsupervised learning algorithm, the algorithm classifies similar types of actions

into cluster units, and determines large clusters as normal actions and small clusters as abnormal actions.

The true/false autonomous decision module judges threats simultaneously with the threat detection module, and re-judges the threats determined by the threat detection module. The judged result is sent to the integrated security policy management module after classifying true and false detection. The integrated security policy management module updates the security policy and sends it to the threat detection module, and the threat determination standard is modified according to the updated security policy. The automatic decision algorithm for true and false detection also uses supervised learning algorithms and unsupervised learning algorithms. The true detection rate is improved through supervised learning algorithm, and the non-detection rate and false detection rate are reduced through unsupervised learning algorithm.

The threat automatic block module blocks the operation of the system or network once the event is judged to be a threat in the threat detection module. In addition, security systems are taken according to the result of the true/false autonomous decision module. Each type of security event is processed by predefined threat response processor step by step, and the processor executes according to the information received from the big data analysis module, threat detection module, and true/false autonomous decision module. For example, an automatic firewall's blocking action is executed for an event having a malicious IP, and this execution action is sent to the integrated security policy management module to update the integrated security policy database.

The integrated security policy management module manages security policies including all security rules and standards processed in the integrated cyber defense platform. When a new event or threat occurs in the module of the integrated cyber defense platform, it is sent to the database through the integrated security policy management module, and when a changed or added security policy also occurs, it is received from the database to the corresponding module of the integrated cyber defense platform. In addition, when a new intelligent threat occurs, the necessary data to configure the learning data is requested to the module, and the received data is sent to the artificial intelligence and big data database.

The database consists of an integrated security policy database, an artificial intelligence database, and a big data database. The integrated security policy database contains security rules, procedures, standards, etc. for the operations by all modules of the platform. When a new or modified threat or security event and new detection mechanism are discovered through the platform's modules, the integrated security policy database is updated through the integrated security policy management module. The artificial intelligence database manages AI algorithms used by modules within the platform and saves data such as learning data. It manages the evolution and change of algorithms to detect new threats or security events as new threat or security event occurs. In particular, it also manages such operations as threat detection/blocking using AI algorithms, malware/domain/IP identification, abnormal behavior auto-blocking, artificial intelligence-based self-mutation, deep learning-based similarity analysis, machine learning-based correlation analysis, real-time threat level analysis, etc. Big data database includes big data collection (big data search, collection, conversion), big data storage (distributed file system, distributed database, distributed system access control, etc.), big data analysis

(distributed parallel processing system, big data analysis language, data visualization) and big data management and saves related data.

4.3 Process of an Integrated Cyber Defense Platform

The modules of the integrated cyber defense platform collect, analyze, and process data and respond to threats as shown in the figure below (Fig. 5).

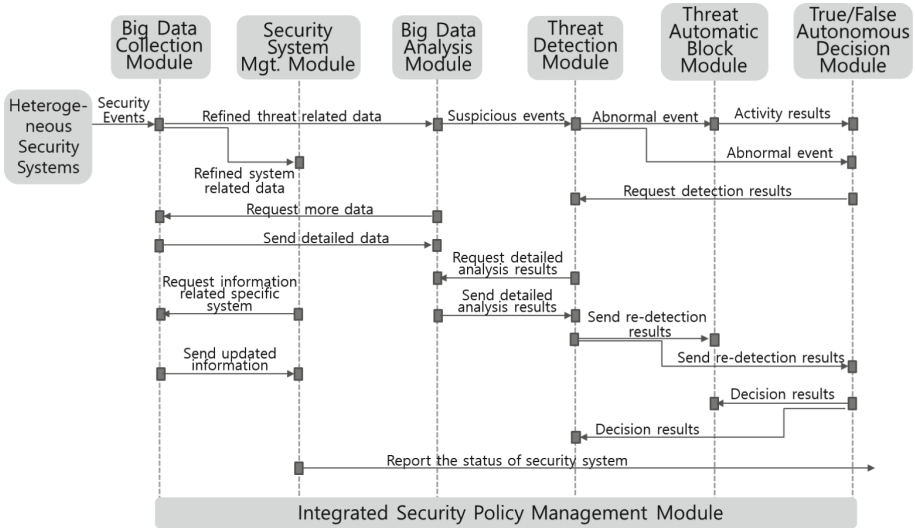

Fig. 5. Process of Modules in an Integrated Cyber Defense Platform

The big data collection module collects abnormal or suspicious events and error data from heterogeneous security systems. Then, such events are refined and sent to the analysis module and security system management module so that the modules of the platform can process them. The security system management module checks the security system in which an error has occurred and identifies the problem. And if action is required, it is reported to the all-source situation room. The analysis module extracts events that can be judged as threats through big data analysis among security events and sends them to the threat detection module. The threat detection module determines abnormal events that can lead to a cyber-attack among suspicious events and sends them to the threat automatic block module and the true/false autonomous decision module. The threat automatic block module blocks the system or network to prevent abnormal events from progressing further into a cyber-attack. The true/false autonomous decision module re-analyzes the detection result determined by the threat detection module to accurately determine whether a threat occurs. If detailed data is needed for judgment, data is requested from the threat detection module. The threat detection module requests the detection result data and additional data to the big data analysis module, executes re-analysis, and sends the result to the threat automatic block module and the true/false autonomous decision module. The big data analysis module also requests the collection

module to collect additional data when the data requested by the threat detection module is insufficient. All execution results from each module are sent to the integrated security policy management module and saved in each database according to the type of data. In addition, the policy management module also performs change management such as modification, addition, and deletion of policies.

5 Conclusion

The proposed integrated cyber defense platform is a security platform customized for military smart units to protect various intelligent mission systems of smart units. Since the network of the military smart unit is composed of a closed network, cyber threats from the outside can be limited. However, if a cyber-attack occurs, such as a supply chain attack or insider threat, the damage will cause enormous damage not only to the unit but also to the all units connected to the unit. Recently, cyber-attack technology has a sophisticated and covert attack form by applying artificial intelligence algorithms. These intelligent cyber-attacks have limitations in protecting them with the existing installed and operating security systems. Therefore, artificial intelligence and big data were applied to the cyber defense platform to quickly detect errors or indications of threats and accurately detect cyber-attack. In particular, we applied big data technology that can quickly collect, analyze, process, and process enormous data generated from various mission systems and security systems. And we also applied supervised/unsupervised learning algorithm to detect threats quickly and accurately and block them preemptively. The true/false autonomous decision function allows to accurately determine the characteristics of a threat by using an artificial intelligence algorithm after detecting a threat.

In the future, it plans to identify the type and form of threats occurring in smart units to strengthen threat detection and true/false autonomous decision function.

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Evaluating Inner Areas Potentials (EIAP 2023)



Projects and Funding in Italian Inner Areas: Learning from the 2014–2020 Programming of the SNAI National Strategy

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Abstract. The first programming of the Italian "National Strategy for Inner Areas" (SNAI) was approved in 2012 and implemented in 2014–2020 with the aim of improving the quality of local essential citizenship services (local public transport, education, social and health services) and fostering the economic development of inner territories, characterised by weak socio-economic contexts. The objective of this research is to analyze numbers, sectors and funding of projects included in the first SNAI programming cycle (2014/2020) in order to support local authorities in the second cycle (2021–2027) which has recently started. In particular, the geographical and thematic distribution of the interventions in each inner area, the allocation of funding and the project status are analysed by processing government and SNAI open data through Exploratory Data Analysis.

The results show the amount of funds and how these have been distributed at national level into different sectors and related projects. This analysis let to understand whether, considering mountain inner areas, the programmed strategies were similar to the national ones or whether they met specific territorial needs. The main spillover of this research is to learn from the previous SNAI programming cycle by highlighting its preliminary outcomes (particularly for mountain inner areas) and addressing possible new or successful projects for future strategies.

Keywords: SNAI · Mountain Inner Areas · public funding

1 Introduction

Italian inner areas have been overshadowed by urban poles for decades causing in these marginal territories progressive loss of services, resources, cultural values, and depopulation [1]. Inner areas have a lower level of accessibility than urban ones due to geomorphological, socio-economic and settlement reasons and require specific planning policies [2, 3]. This difference between inner areas and cities created disparities also in equity and social inclusion, in both public and private transport [4]. The ESDP (European Spatial Development Perspective) has improved the level and range of policies, adopting a regional approach [5], trying to foster/encourage polycentrism [5–7].

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In Italy, the Minister of Economic Development approved in 2012 the "National Strategy for Inner Areas" (SNAI), a territorial policy with the aim of –still todayre– balance the local essential citizenship services (local public transport, education, social and health services) and, at the same time, to foster the economic development and enhance the natural and cultural heritage of these areas. SNAI's long-term goal is to keep these areas alive by counteracting the depopulation process. The selection of the areas began in 2013 and the criteria were based on the "distance" from essential services and on the difficulty to reach the Poles (cities that offer a series of services such as schools, a hospital and a railway station). In fact, based on the distance from these Poles, it has been defined four diverse types of areas: Belt Areas (20 min by car from the Pole), Intermediate Areas (up to 40 min), Peripheral Areas (up to 75 min) and Ultraperipheral Areas (over 75 min) (https://opencoesione.gov.it/en/SNAI).

In the first SNAI cycle (2014 -2020) 72 areas were selected, including 1.060 Municipalities, with a population lower than 2 million inhabitants (Istat data, 2020). These areas occupy a wide territory of approximately 51.000 km^2 and represent 13.4% of all Italian Municipalities, 3.3% of the national population and 17% of the entire national surface [8]. The total funding amount of the program was almost 1,167 million euros, splitted into:

- 266 million euros (from the resources allocated by Laws n. 147 of 2013, n. 190 of 2014, n. 208 of 2015 and n. 205 of 2017);
- 712 million euros (from the resources allocated by FESR, FSE, FEASR e FEAMP, Eu funding programmes);
- 132 million euros (from other public resources);
- 57 million euros (from private resources).

In the last years, the evaluation and selection processes of Inner Areas have been analysed in numerous studies. Some researchers analysed or applied different kind of indicators to integrate the evaluation criteria defined by SNAI used for the classification of the new inner areas, such as Territorial Capital [9], community-based cooperatives [10], marginality linked to mobility, demographic and socio-economic conditions [11], while others studies deepened the critical points in certain areas and related them to the planned strategies. Moreover, in 2020 the "B4R-Branding for Resilience" research project (PRIN 2017- Youth Line) was funded by the Italian Ministry of University and Research (MUR) to explore the potential for resilient development of territories and communities in four Italian inner areas [13–15].

In 2020, after the State budget law for the fiscal year (art.1 c. 314 Law 27 December 2019 n. 160) and with the Decree Law dated 14 August 2020, n. 104 (art. 28), the SNAI was strengthened and expanded with new funds, which amounted to 172 million euros for the 2021–2027 cycle. Therefore, 43 new inner areas were selected and funded, and each of them was designated to receive around 4 million euros [15]. The approval process of the new Inner Areas was concluded with the CTAI (Internal Areas Technical Committee) of 29 September 2022; therefore, several local authorities are currently managing complex processes to identify their local strategies and the related activities to be funded, even if they cannot totally learn from the results of the first SNAI programming cycle (2014–2020), which are not fully known. This lack of knowledge can be overcome by critically analysing the information at national scale, which describe the projects and

the investments implemented in the past SNAI programming cycle that are still in the development phase.

The objective of this research is to analyze the numbers, sectors and funding related to the projects of the first SNAI programming cycle (2014/2020) in order to identify (particularly for mountain inner areas) evidence and specifications from the past, to support local authorities in the second cycle (2021–2027), which has recently started.

The paper is structured as follows: the methodological approach (structured in 4 phases and related sub-phases) is illustrated in Sect. 2; Sect. 3 presents the Data Sample and the related consulted materials and analysed data. Section 4 contains results and discussions on similarities and differences deriving from the analysis of number of projects, sectors and funding, and from a comparison between mountain inner areas and the whole reference sample. Lastly, Sect. 5 shows the concluding remarks.

2 Methodological Approach

The methodological approach is based on an Extract-Transform-Load (ETL) process, divided into four main phases which include different sub-phases of application. Figure 1 shows the subsequent phases: Goal definition (1), Data collection and preparation (2), Data Analysis (3) and Results Interpretation (4).

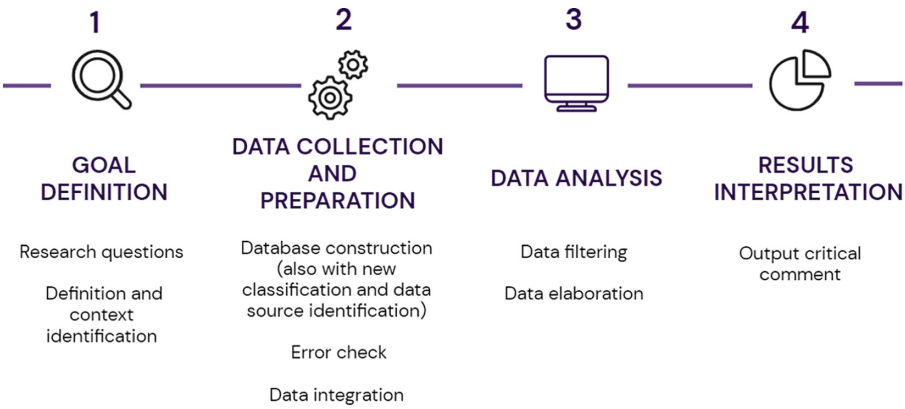

Fig. 1. The 4-phase methodological approach based on ETL. (Source: authors' elaboration)

Goal Definition. In the first phase, the main objective of the study and the different research questions have to be defined. This is necessary to narrow the research direction and context. Thereafter, materials and data sources can be identified.

Data Collection and Preparation. In the second phase, data must be collected, armonized and stored in databases. It is important to refine and armonize collected data to make them as suitable as possible by checking and correcting different kind of errors

(if any) and by integrating any missing data. Through these sub-phases the database is built and processed in order to be able to carry out subsequent analyses.

Data Analysis. In the third phase, information and data can be filtered and selected in order to build separate data sample, suitable for the explanatory analyses. Data filtering and selection process can be applied both at national and at the focus level. Outputs of this phase are results to be interpreted in the next step.

Results Interpretation. In the last phase, the results support the definition of some concluding critical comments and possible developments of the research. This phase can lead to find evidences to support efficient and effective territorial strategies or actions for local communities.

3 The First SNAI Programming Cycle: Data Sampling on Funded Projects

The 72 inner areas designated in the first SNAI programming cycle (2014–2020) represent the case study of this research: 23 of them are in the North, 28 in the Center and 21 in the South Italy. These areas cover 60% of the entire surface of the national territory and include 52% of the Italian Municipalities, where 22% of the total population live.

In order to analyse the projects funded during the first SNAI programming cycle a data sample was built by collecting data from three open data sources: the Agency for Territorial Cohesion (SNAI section), the Opencoesione portal, the National Institute of Statistics (ISTAT):

1. Agency for Territorial Cohesion (SNAI section): from this website (https://www.agenziacoesione.gov.it/strategia-nazionale-aree-interne/), it is possible to download data related to selection processes, planning strategies, subsequent formalization of the strategy. More precisely, the available data are: Annual report for inner areas (2020 update); Map of inner areas; List of municipalities belonging to each inner areas; Guide to «Open Diagnosis» indicators;
2. Opencoesione portal: this website (www.opencoesione.gov.it) is an open government initiative on cohesion policies in Italy, to promote the effectiveness of interventions through the publication of data on funded projects and widespread civic participation. The published datasets are enclosed in a single document that contains all the information relating to the reference projects. This file (updating date: 30th June 2022) contains about 1700 projects described by 203 variables, such as the conformation of each inner area (region, province, municipalities belonging to the areas); the eleven synthetic sectors used to catalogue the projects; a brief description of each project; funds divided according to type (private, public, regional, province, municipality, European Union, etc.); composition of public funds (FESR, FSE, FEASR e FEAMP); the progress of each project and the amount of its funds ("work progress"). Some inconsistencies have been identified in the Opendata; therefore, data has been checked and eventually integrated. Nevertheless, since the database has an official source eventual incompatibilities of filling are not considered in this first step of the analysis. New graphs and data have been updated (updating date: 31st October

2022) and uploaded on the website in February 2023 (not considered in the following analyses);

3. National Institute of Statistics (ISTAT): from this website (https://www.istat.it/it/) it is possible to download a plenty of data at municipal level. ISTAT is a public research organization and is the main official statistics' producer to support citizens and public decision makers. Therefore this data source doesn't refer to specific strategies and projects, but provides data on a national, regional, provincial and municipal level. Specifically, the authors used this portal to integrate the missing data in the previous portals mentioned on a municipal scale. Specifically, for this research the coherent data are building density, number of inhabitants, altitude, per capita income (Per capita amount of gross national product supposedly produced by a person in a certain period of time. It coincides with the worker's average annual salary and its unit of measurement is the ratio between the currency and the inhabitant) (updated date: 1 January 2022).

The initial lists of 1.692 funded projects and related information was integrated by including in the data sample also the Valle Maira and Val Grana inner area (Piedmont Region), that was missing. Therefore, data from the abovementioned data sources were integrated in a data sample consisting of 1.699 records (funded projects), described by 203 variables. Table 1 shows the main variables of the data sample, some of which were newly created.

Table. 1. Data structure of the main variables (Source: Authors' elaboration)

Data structure	Data content	Data value		Data structure
Field name		vocabulary	Field name	
Projects' sector	Project classification (and research) themes: aggregation of sectors and fields of intervention	closed	Environment, Administrative capacity, Competitiveness of companies, Culture and tourism, Energy, Social inclusion and health, Education and training, Employment and work, Digital networks and services, Research and innovation, Transport and mobility	Opencoesione data

(*continued*)

Table. 1. (*continued*)

Data structure	Data content	Data value		Data structure
Field name		vocabulary	Field name	
Italian Geographical Areas	Geographic location of each inner area	closed	North, Centre, South	Authors' elaboration on Opencoesione data
Project status	Work progress of each project	closed	Completed, in progress, Settled, Not started	Opencoesione data
Total funds	Public (FESR, FSE, FEASR e FEAMP) and private funds	open	Euros	Authors' elaboration on Opencoesione data
Percentage of funds	Percentage of funds for each project's sector out of the total	open	%	Authors' elaboration on Opencoesione data
Percentage of number of projects	Percentage of number of projects for each project's sector out of the total	open	%	Authors' elaboration on Opencoesione data
Average altitude	Average altitude of all municipalities of each inner area	open	Meters (above sea level)	Authors' elaboration on ISTAT data
Building density	Relationship between density and built morphology	open	Building / m^2	ISTAT data
Number of inhabitants	Number of inhabitants of each inner area (sum of inhabitants of all the municipalities)	open	inhabitants	ISTAT data
Per capita ratio	Amount of gross national product per capita in a certain period of time	open	€/inhabitants	ISTAT data

Lastly, from the whole data sample a sub-sample limited to projects located in mountain inner areas was extracted, to compare the strategies of those areas with the national ones: it consisted 903 projects referred to 32 mountain inner areas.

4 First SNAI-Funded Projects: Interventions Distribution, Funding Allocation and Implementation Progress

The whole data sample consisting of the 1.699 projects referred to the 72 inner areas was analysed to study the first SNAI programming cycle (2014/2020), in terms of geographical and thematic distribution of the interventions, allocation of funding and progress of

implementation. The geographical division in different Regions was assumed to make some comparisons on the distribution and allocation of funds because Italy presents territories with quite different economies, urban and administrative development. Firstly, the Italian Regions were grouped into three main areas: North Italy (Valle d'Aosta, Piemonte, Liguria, Lombadia, Trentino-Alto Adige, Veneto and Friuli-Venezia Giulia); Centre Italy (Emilia-Romagna, Toscana, Marche, Lazio, Umbria, Molise, Abruzzo and Sardegna); South Italy (Basilicata, Calabria, Campania, Puglia and Sicily). Secondly, a division based on the average altitude of each inner area allowed to identify only Mountain Inner Areas (with an average altitude of 800 m above sea level). This focus was necessary to distinguish and understand the dynamics of mountain territories, which have different morphological, geographical, productive, socio-economic and socio-demographic characteristics (Table 2).

Table. 2. Mountain inner areas with altitude above of 800 m (above sea level) – (Source: Authors' elaboration)

Italy Main Areas	Mountain Inner Areas and Regions
North	• Liguria (Beigua and Unione Sol, Antola Tigullio), Lombardia (Alta Valtellina, Appennini Lombardi Oltre Po Pavese, Valchiavenna), • Piemonte (Val di Lanzo, Val d'Ossola, Valli Maira and Grana), • Trentino-Alto Adige (Tesino, Val di Sole); • Valle d'Aosta (Bassa Valle Valley, Grand Paradis), Veneto (Comelico, Spettabile Reggenza), • Friuli Venezua Giulia (Dolomini Friulane)
Center	• Abruzzo (Basso Sangro – Trigno, Alto Aterno Gran Sasso Laga, Valle del Giovenco - Valle Roveto), • Emilia-Romagna (Alta Valmarecchia, Appennini Emiliani), • Marche (Alto Maceratese, Ascoli Piceno), • Molise (Alto Medio Sannio, Fortore, Mainarde, Matese), • Toscana (Casentino Valtiberina)
South	• Basilicata (Area Interna Mercure - Alto Sinni - Val Sarmento); • Calabria (Sila e Presila); • Campania (Alta Irpinia); • Sicilia (Nebrodi, Valle del Simeto)

In each Italian Region there is a different number of inner areas: 2 in Trentino-Alto Adige, Valle d'Aosta and Sardegna; 3 in Friuli-Venezia Giulia, Marche, Toscana and Umbria); 4 in Basilicata, Calabria, Campania, Emilia-Romagna, Lazio, Liguria, Lombardia, Molise, Piemonte, Puglia and Veneto); 5 in Abruzzo and Sicilia.

The whole data sample was analysed by means of pivot tables and exploratory summary statistics on the basis of different variables: total public funds, private funds, number of projects, prevalent sectors, project status, geographical area and inner area average altitude.

All the analyses were perfomed at national level and then were focused on mountain inner areas. Figure 2 shows the distribution of public funds in each considered sector at national level, in comparison with the total number of projects.

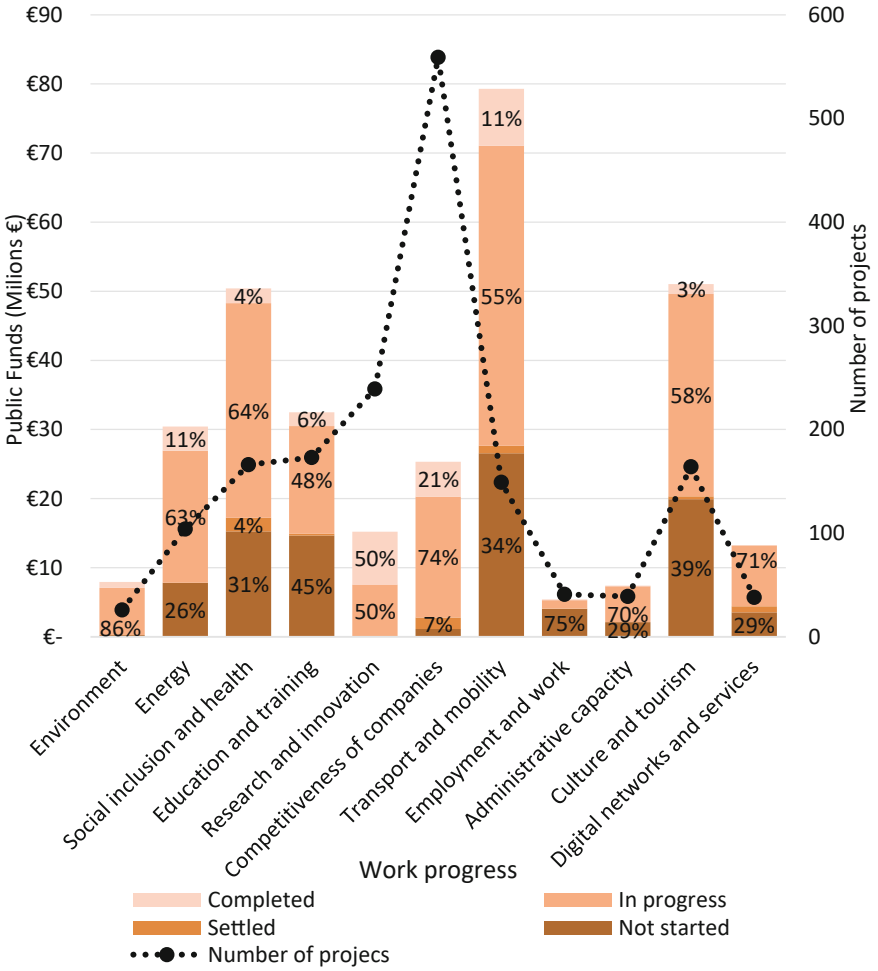

Fig. 2. National level – Public funds based on the 11 sectors – (Source: Authors' elaboration on Open Coesione data)

Firstly, it emerges that the number of projects is not directly proportional with the amount of funds received. For example, the sector "Competitiveness of companies" had a high number of projects (559) but less than 20 million euros for funds; on the contrary, funds related to "Transport and mobility" were around 80 million euros but with a limited number of projects (149). The highest funds (between 50 and 80 million euros) were allocated to projects related to "Transport and mobility", "Culture and tourism" and "Social inclusion and health", while the lowest funds (less than 10 million) were designated for projects related to "Protection and development of the environment", "Employment and work" and "Administrative capacity".

Figure 3 shows the distribution of public funds in each considered sector in the selected mountain inner areas and presents the total number of projects.

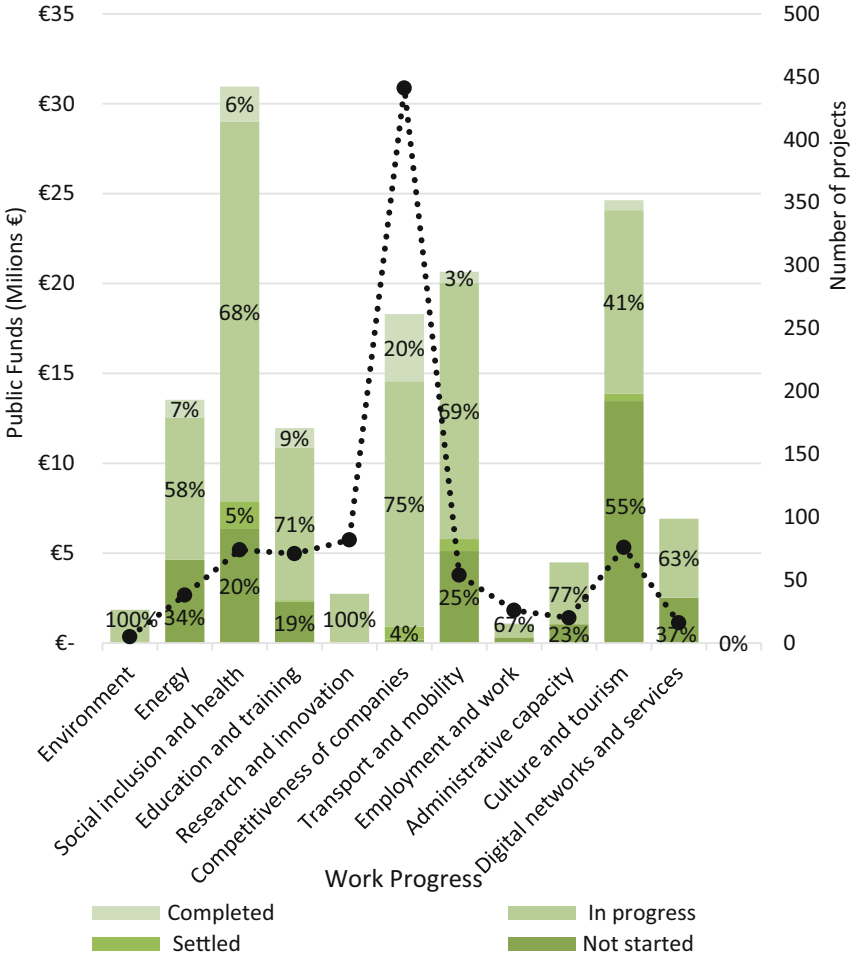

Fig. 3. Mountain Inner Areas – Public funds based on the 11 sectors – (Source: Authors' elaboration on Open Coesione data on Open Coesione data)

It is evident that by considering the number of projects, the sector with the highest value was "Competitiveness of companies" followed (with a difference of about 250 projects) by "Research and innovation", "Social inclusion and health" and "Culture and tourism"; otherwise, the "Environment" and "Employment and work" sectors presented the lowest numbers of projects. Furthermore, as already noted at national level, also in the mountain inner areas, most of funds (between 20 and 35 million euros) were allocated to projects related to "Transport and mobility", "Culture and tourism" and "Social inclusion and health". However, it is worth mentioning that in the mountain inner areas the sector that attracted most funds was "Social inclusion and health" (23% of total funding). The lowest funds (less than 5 million euros) were allocated for projects related to the protection and development of "Environment", "Employment and work" and "Administrative capacity". The "Competitiveness of companies" was instead in the medium-high range. The main sectors based on number of projects are coeherent with the results at national level: "Competitiveness of companies" (26%), "Research and innovation" (9%) and, at the same percentage, "Culture and tourism" (8%), "Social inclusion and health" (8%) and "Education and training" (8%).

In both charts (Figs. 2 and 3) it emerges that the completed projects are a minority (percentages between 0% and 21%, except for the "Research and Innovation" projects that are 50% completed at national level), while most of the projects are "ongoing", even if three years have already passed since the end of the 2014–2020 cycle. It is worth noting that there is still a high percentage of projects not started, even reaching percentages of 75%, at national scale, in the "Employment and work" sector, and 55% in mountain inner areas in the "Culture and tourism" sector.

Table 3 summarises the main results from the analysis of the whole data sample and the sub-sample related to mountain inner areas, by highlighting detailed data for the North, Centre and South of Italy. Table 3 highlights the received funds (divided between public and private) and the prevailing sector (by the number of projects and by the amount of received funds).

It is interesting to notice that at national level inner areas are almost equally distributed in the North (32%), Centre (39%) and South (29%) of Italy, while, for geomorphological reasons, mountain areas are concentrated in alpine and appenine regions in the North (22%) and Centre (17%). The funded project are concentrated in the Centre (43%) at national level, while in the considered mountain inner areas they are pairly concentrated in the North (44%) and Centre (43%). The total funds (public and private) are fairly evenly distributed at national level, while focusing on mountain areas more than 50% of them are allocated in the North. Furthermore, it interesting to notice that most of the public funds were distributed in the North and South (72%), while private funds are extremely limited and prevail in the North and in Centre (2,7%) both at national scale and in mountain inner areas (about 2–5%). In general, it is interesting to notice that at national level inner areas in the South of Italy received a fair amount of funding (125.362.589 €) despite a small number of projects submitted (349). On the other hand, in the Northern inner areas more that 600 projects were presented and funded with a similar amount of funding (126.630.868 €). In the mountain inner areas more that 300 projects were funded in the North and Centre (respectively 44% and 43%), with significantly different funds (81.967.102 € in the North and 34.541.436 € in the Centre).

Table 3. Descriptive statistics of total number of projects and funds, in Italian inner areas (whole sample) and in mountain inner areas (sub-sample). (Source: Authors' elaboration on Open Coesione data)

	ITALIAN INNER AREAS WHOLE SAMPLE				MOUNTAIN INNER AREAS SUB-SAMPLE			
	North	Centre	South	Italy	North	Centre	South	Mountain areas
Number of Inner Areas	(32%) 23	(39%) 28	(29%) 21	**(100%) 72**	(22%) 16	(17%) 12	(6%) 4	**(44%) 32**
Total number of projects	(36%) 619	(43%) 730	(21%) 349	**(100%) 1698**	(44%) 397	(43%) 391	(13%) 115	**(100%) 903**
Total funds (public + private)	(38%) 126.630.868 €	(25%) 84.559.479 €	(37%) 125.362.589 €	**(100%) 336.552.937 €**	(56%) 81.967.102 €	(23%) 34.541.436 €	(21%) 30.654.553 €	**(100%) 147.163.092 €**
Public funds	*(35%) 117.577.548 €*	*(22%) 75.544.285 €*	*(37%) 125.102.312 €*	***(95%) 318.224.146 €***	*(53%) 78.649.702 €*	*(19%) 27.895.353 €*	*(21%) 30.570.676 €*	***(93%) 137.115.732 €***
Private funds	*(2,7%) 9.053.319 €*	*(2,7%) 9.015.194 €*	*(0,1%) 260.276 €*	***(5%) 18.328.790 €***	*(2%) 3.317.400 €*	*(5%) 6.646.083 €*	*(0,1%) 83.876 €*	***(7%) 10.047.360 €***

Table 4 divides data of the whole sample and the sub-sample of mountain inner areas in the same three geographical areas (North, Centre, South of Italy) to analyse the principal sectors based on number of projects and received funds.

By analysing both the whole sample of Italian inner areas and the mountain inner areas sub-sample, the prevalent sector based on the number of projects is "Competitiveness of companies" (CC) in the North and Centre (covering around 30% of the total number of projects), while in the South it is "Transport and Mobility" (TM). By analysing the funds received, the prevalent sectors are different: "Culture and tourism" (CT) in the North, "Social inclusion and health" (SH) in the Centre and "Transport and mobility" (TM) in the South. The sectors that received the most funds ("Social inclusion and health", "Transport and mobility", "Culture and tourism") are in a medium-high range for funds, with an average fund for a project between 232.000 € and 646.000 € (at national level) and 358.543 € and 391.000 € (in the mountain inner areas). The sectors with the highest number of funded projects, instead, have lower funds (clearly with a lower average fund for a project between 30.000 € and 646.0008 € (at national level) and 20.000 € e 66.000 € (in the mountain inner areas). Considering the whole sample, the most funds (19%) are provided in the South for 92 projects related to "Transport and Mobility" (TM): this due to important new infrastructure projects in Basilicata (Strategia Nazionale delle Aree Interne, Strategia Area Mercure – Alto Sinni – Val Sarmento, programmazione 2014–2020, https://www.agenziacoesione.gov.it/wp-content/uploads/2020/11/Strategia_AI_Mercure_-21.02.2020.pdf) and Puglia (Strategia Nazionale delle Aree Interne, Relazione annuale sulla strategia Nazionale per le aree

Table 4. Descriptive statistics of prevalent sectors and prevalent funds, in Italian inner areas (whole sample) and in mountain inner areas (sub-sample). (Source: Authors' elaboration on Open Coesione data)

	ITALIAN INNER AREAS WHOLE SAMPLE				MOUNTAIN INNER AREAS SUB-SAMPLE			
	North	Centre	South	Italy	North	Centre	South	Mountain areas
Prevalent Sector based on the number of projects	CC*	CC*	TM*	**CC***	CC*	CC*	TM*	**CC***
Number of prevalent sectors projects	(16%) 273	(17%) 283	(5%) 92	**(33%) 559**	(12%) 200	(14%) 239	(2%) 31	**(26%) 441**
Public funds of prevalent sector projects	(5%) 15.977.769 €	(3%) 8.470.578 €	(19%) 59.488.863 €	**(8%) 25.326.380 €**	(4%) 13.314.629 €	(2%) 4.913.443 €	(4%) 12.112.684 €	**(6%) 18.306.104 €**
Average fund for a project of the prevalent sector (Number of projects)	58.526 €	29.931 €	646.618 €	**45.306 €**	66.573 €	20.558 €	390.731 €	**41.510 €**
Prevalent Sector based on funds	CT*	SH*	TM*	**TM***	CT*	SH*	TM*	**SH***
Number of prevalent funds projects	(3%) 58	(4%) 75	(5%) 92	**(9%) 149**	(5%) 48	(2%) 21	(3%) 31	**(8%) 74**
Public funds of prevalent funds project	(7%) 22.311.482 €	(5%) 17.376.449 €	(19%) 59.488.863 €	**(25%) 79.282.020 €**	(5%) 17.156.934 €	(2%) 7.529.406 €	(4%) 12.112.684 €	**(10%) 30.952.774 €**

(*continued*)

Table 4. (*continued*)

	ITALIAN INNER AREAS WHOLE SAMPLE				MOUNTAIN INNER AREAS SUB-SAMPLE			
	North	Centre	South	Italy	North	Centre	South	Mountain areas
Average fund for a project of the prevalent sector (funds of projects)	384.680 €	231.685 €	646.618 €	**532.094 €**	357.436 €	358.543 €	390.731 €	**418.280 €**

* CC: Competitiveness of companies; TM: Transport and mobility; CT: Culture and tourism; SH: Social inclusion and health

interne, 2020, https://www.agenziacoesione.gov.it/wp-content/uploads/2021/11/Relazione-CIPESS-2020_finale.pdf). As proof of this, the prevalent sector covers only 9% of all national projects, 5% of which are in the South.

The latest results are related to a specific focus on three mountain inner areas, selected on the basis of the highest altitude according to the geographical position (North, Central, South):

- Grand Paradis (Aosta Valley, Northern Italy) (https://www.agenziacoesione.gov.it/wp-content/uploads/2020/10/APQ_AREE_INTERNE_GRAND_PARADIS.pdf);
- Mainarde (Molise, Central Italy) (https://www.agenziacoesione.gov.it/wp-content/uploads/2020/11/Molise-Mainarde-strategia.pdf);
- Mercure - Alto Sinni - Val Sarmento (Basilicata, Southern Italy) (https://www.agenziacoesione.gov.it/wp-content/uploads/2020/11/Strategia_AI_Mercure_-21.02.2020.pdf).

Figure 4 shows, for the three selected mountain inner areas, public funds and the number of projects analysed by the 11 sectors.

First of all, it is interesting to notice that the analyses on these three selected mountain areas highlight very different situations, in terms of sectors of intervention both for funds and number of projects, reflecting the specificity of each territory. The sectors present in all areas are "Transport and mobility" and "Culture and tourism". Gran Paradis and Mainarde inner areas have also similar funds for the "Administrative capacity" sector (around 10%), while in Mercure - Alto Sinni - Val Sarmento this sector has extremely limited funds, equal to € 1,314,580.00, corresponding to a very small percentage that does not appear in the chart. In Gran Paradis inner area, the "Social inclusion and health" sector covers the largest percentage (50%) of total public funds and the 25% of total projects. In Mainarde inner area, the 52% of funding was provided for the "Transport and Mobility" sector, as in Mercure - Alto Sinni - Val Sarmento inner area, where this sector attracted the 59% of public funds. Results also show that in these 3 selected areas the following sectors are totally absent: "Environment", "Competitiveness of companies" and "Research and Innovation".

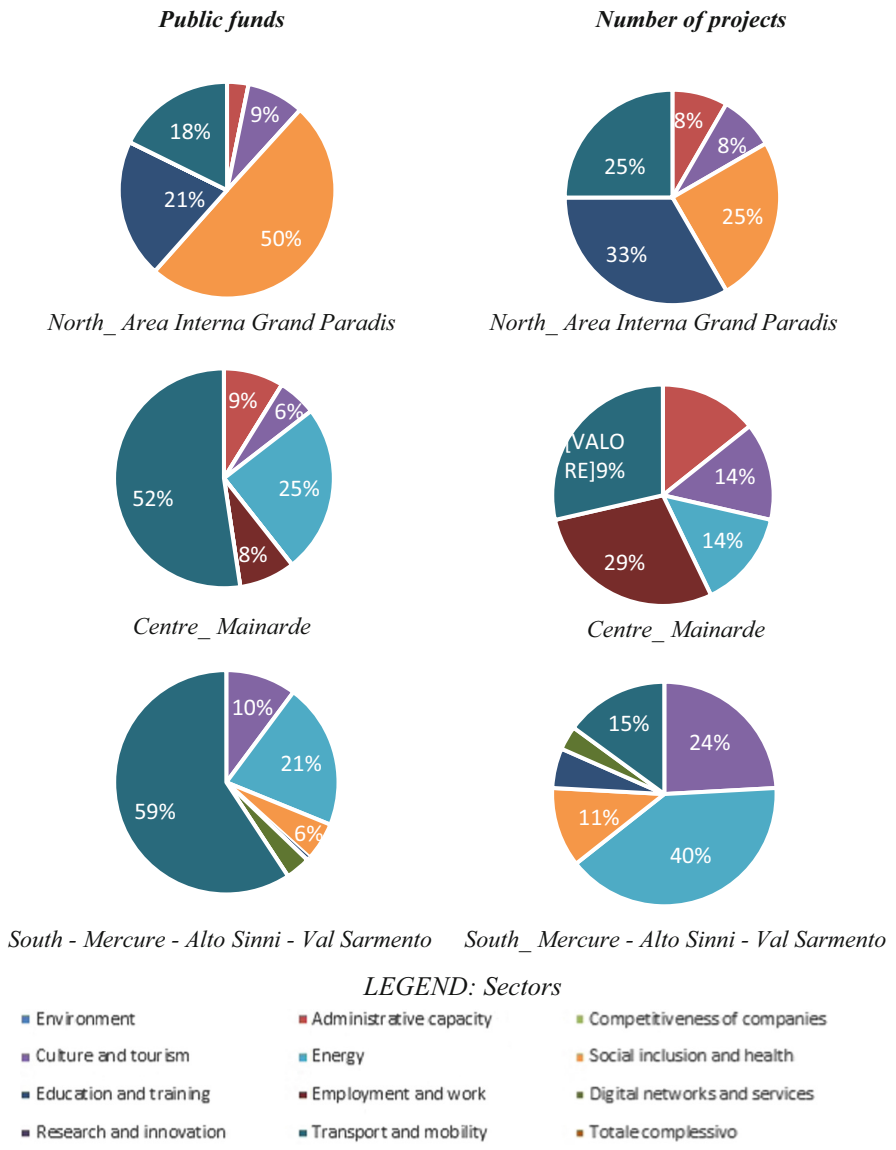

Fig. 4. Selected mountain inner areas: Public funds and Number of projects based on the 11 sectors. (Source: Authors' elaboration)

5 Discussion and Conclusion

This research was based on a detailed data sample built by collecting data from three open data sources (the Agency for Territorial Cohesion-SNAI section, the Opencoesione portal, and the National Institute of Statistics-ISTAT): it included 1.699 projects funded

during the first SNAI programming cycle (2014/2020), referred to 72 inner areas. A subsample consisting of 903 projects related to 32 mountain inner areas was extracted, to compare the strategies in terms of geographical and thematic distribution of the interventions, allocation of funding and progress of implementation. Exploratory Data Analyses were conducted to understand whether the planned strategies in mountain inner areas were coherent with those planned at national level or whether they met specific territorial needs, and thus to support local authorities in the second SNAI cycle (2021–2027) which has been recently launched.

Results showed the amount of funds and how these were distributed into different sectors and related projects, both at national level and in mountain areas, by highlighting different lacks and prevalences. In particular, results showed that at national level the average fund for a single project is 532.094€, the average fund received for a single project is 198.205,50 €. Furthermore, the average number of projects for each inner area is 24. Focusing on mountain areas the average funds (public and private) is 4.598.843 €, while the average funds received for each project is 162.971 € and the average number of projects per mountain area is 32.

At national level, the prevalent sector based on the number of funded projects is "Competitiveness of companies", while the sector that received the highest amount of funds is "Transport and Mobility" (funds around 80 milions euros); the sectors with the most advanced project progress are "Research and innovation" and "Business competitiveness" (respectively with 50% and 21% of completed projects).

Results related to mountain inner areas are slightly different. The prevalent sector is again "Competitiveness of companies", while the one that received the highest amount of funds is "Social inclusion and health" (funds around 30–35 milions euros); the sector with the most advanced project progress is "Competitivness of companies" (with 20% of completed projects). Results also indicated that mountain areas had a significant shortage of funds in the following sectors: "Environment", "Research and innovation", "Employment and work" and "Administrative capacity". A weak attention to projects related to environmental issues is partly surprising because the mountain areas are usually rich in natural areas that should be protected and enhanced. Furthermore, the lack of funding in the "Employment and work" sector confirms the problems related to decreasing number of young people living in those areas and to the often difficult development of companies (work and innovation); the limited funds in "Administrative capacity", instead, highlights the high administrative fragmentation of these minimal territorial areas.

Lastly, the analyses of three specific mountain inner areas (located in northern, central and southern Italy), selected as key references, confirm that inner areas' high complexity and territorial context specificity need to be tackled with a tailor-made approach, by applying a shared methodology and avoiding pre-defined and biased processes.

Therefore, it can be concluded that this research could support local authorities in answering some of the following questions: *i)* How should the new inner mountain areas address their strategies in relation to the project sectors to be considered? *ii)* How many funds can be allocated for each project? *iii)* On which sectors should the most funds be allocated? *iv)* What design strategies could be selected (or excluded)?

By analysing the numbers, sectors and funding related to the projects of the first SNAI programming cycle it is possible to learn from its results and thus address possible

new or successful projects for future strategies to be implemented in the second cycle (2021–2027).

Due to the interest and relevance of these research topics, in the context of the new programming cycle, the research could go beyond these preliminary results in view of potential future developments, which could integrate further open data from various sources and develop a specif context-based approach to define different strategies and interventions in the SNAI inner areas.

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The SAVV+P Method: Integrating Qualitative and Quantitative Analyses to Evaluate the Territorial Potential

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Abstract. Italian rural territories are often fragile socio-economic contexts characterized by limited local essential services (local public transport, education, social and health services), high depopulation and few young inhabitants. The present research moves in the framework of the National Strategy for Inner Areas (SNAI), an innovative Italian policy that counteract marginalization and demographic decline, by funding projects to create new chances for local development and territorial cohesion. By assuming the SAVV method to explore fragile territories and identify the most vulnerable and vibrant areas within the considered territory, the new evaluation method SAVV+P is proposed to classify the territorial potential in 3 different categories (Moving/Evolving/Starting). Both methods (SAVV and SAVV+P) were tested in the Alta Valsesia area, located in northern Piedmont (Italy), which is one of the inner areas studied within the "B4R Branding4Resilience" research project. The aim of this study is to analyse the developing potential for new cultural-tourist infrastructures for the enhancement of the Alta Valsesia municipalities. Results demonstrated how the integration between quantitative and qualitative analyses could effectively support the identification and development of new opportunities and enhancement strategies to find unexpressed potential for these fragile territories. Results showed also how the considered municipalities could change their condition by considering their potential assets and triggers.

Keywords: Inner Areas · Index-based evaluation method · Territorial potential

1 Introduction

For more than a decade, in Italy the attention was focused on the theme of the enhancement of inner areas, with the aim of countering the marginalisation and demographic decline of these territories [1]. The National Strategy for Inner Areas (SNAI 2013) launched a complex process of analysis of marginal territorial contexts and led, in 2019,

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to the identification of 72 Inner Areas (including approximately 1,000 municipalities, with a resident population of about 2 million inhabitants). In these selected territories the Italian Government allocated more than 590 million euro (First programming cycle), to foster local development processes and improve the level of infrastructure and services. The first SNAI classification was updated in 2022, by including other 43 areas for which the government allocated a total of 310 million euro (Second programming cycle - Regional Council Resolution n. 28/5251 of 21 June 2022). The evaluation process that led to the identification of the areas was carried out by the Regions, in agreement with the Inner Areas Technical Committee, through a public investigation, whose outcome was accompanied by a document (the Open Diagnosis) containing an updated picture of the social, demographic, economic situation and the presence of essential services [2]. Therefore, a punctual and articulated assessment (structured in 9 survey areas and carried out on the basis of more than 90 indicators) allowed to define the marginalities of the territories, with the aim of targeting public resources towards the most distant areas from the expected level of infrastructures and services represented by the pole-centers [3].

On the one hand, *vulnerability*, *fragility* and *marginality*, are very often used keywords in theoretical and applied research in relation with territorial, suburban and rural areas [4–10]. Otherwise, the topic of *territorial resilience,* declined also at the rural, small centers and non-urban scale, has been recently studied and investigated [11]. On the other hand, *vitality, vibrancy* and *quality of life* are keywords more related to urban areas, where most population live and aggregate around facilities, public services and activities [12, 13]. Authors also dealt with these issues in previous studies linked to the "B4R - Branding4Resilience" research project [14–16], by taking up the challenge of overturning the logic: no longer analysis and assessment of vulnerabilities but of the vibrancy, from a positive point of view, to revitalise and enhance inner territories [17–19].

This paper proposes an integration of the SAVV method created by the authors to classify territories as Sleeping, Active, Vibrant or Vulnerable and to identify and define strategies, policies and actions oriented towards local development and repopulation [20]. The novelty and the aim of this paper is based on the addition (downstream of the quantitative analyses at the basis of SAVV) of qualitative analyses, able to include in the evaluation of inner areas potential additional information and knowledge not present in open databases or government web portals. In this way, the initial classification derived from the application of SAVV is integrated with position vectors, representing specific potential assets and triggers (SAVV+P method). The final objective is to support local authorities in defining priority policies and interventions, correctly managing all levels of existing knowledge to make territories more competitive, attractive and vibrant for new inhabitants, tourists and economic operators.

Assuming the theoretical framework on territorial vulnerability/vibrancy, the paper describes the new SAVV+P evaluation method (Sect. 2) and its application to the case study of Alta Valsesia (Sect. 3), that is the focus area of the Politecnico di Torino Research Unit (Polito RU) in the B4R research project and part of the new inner area "Valsesia" (in 2022 designated by the Italian Ministry of Territorial Cohesion in the context of the SNAI programming 2021–2027). Based on the main general research objective of B4R

project, the findings of a series of direct qualitative analyses were integrated (Sect. 4) to calculate potential assets and triggers and thus define new territorial potentialities. Some exploratory results (the definition and the length of position vectors) are illustrated in Sect. 5, while possible future developments are discussed in the conclusion, which emphasises the flexibility of use and adaptability of the proposed new evaluation method also in other contexts.

2 Methods

The SAVV+P method presented here derives from a methodological approach consisting of 9 phases divided into further sub-steps based on a knowledge management process which support the transformation of large quantities of data into information and then into knowledge [17–20]. A qualitative-quantitative analyses integration is presented here to allow the evaluation of potential assets and potential triggers in different territorial contexts. Figure 1 presents the multi-modal methodological scheme at the base of the application of SAVV+P.

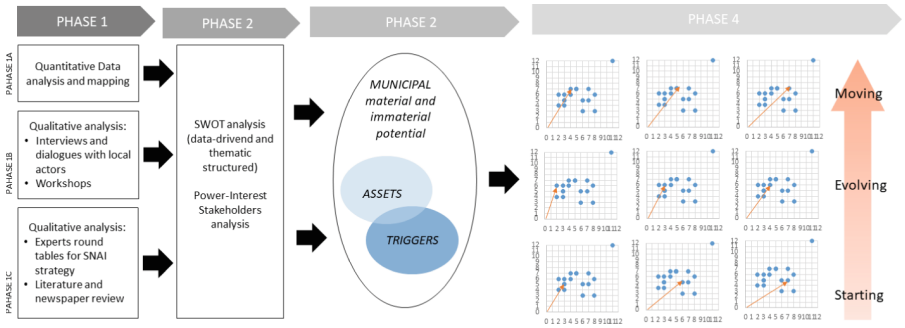

Fig. 1. The SAVV+P method scheme. (Source: Authors' elaboration)

Phase 1. The quantitative analyses and mapping (phase 1A, more developed in previous research as the basis of the SAVV methodology [20]), are based on open data, collected and structured in a geographical database. These quantitative analyses are integrated to qualitative ones (phases 1B and 1C), based on data not present in open databases and collected from other sources, such as interviews and surveys, literature and press review, meetings with local administrators and stakeholders.

Phase 2. All collected and georeferenced data deriving from both quantitative and qualitative analyses can be analysed by applying the SWOT analysis and the Stakeholder Power-Interest analysis. The SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis is an approach used to evaluate companies, territories, projects' competitive position and to develop their strategic planning. SWOT analysis assesses internal and external factors, as well as current and future potential to develop strategies and projects [21]. The Power-Interest Stakeholder analysis classifies all the subjects (organizations and individuals) who are potentially involved in the development process, who

are influenced by it, who have influence or power over it, or who have an interest in its positive or negative conclusion [22, 23].

Phase 3. The results of these two analyses must be transformed, in Phase 3, into potential municipal assets and triggers, which could therefore guide the transformation and development of municipalities/territories according to their specific potentialities. This evaluation is based on the calculation of *Asset* Index and *Trigger* Index, according to the SAVV method [20], and therefore allows a possible new classification of potentialities. Territorial elements classified as *Potential Assets* refer to those elements mainly "static" that needs to be transformed, re-activated or enhanced. Instead, territorial elements classified as *Potential Triggers* represent dynamic events, actions and development drivers that can positively transform the current state of the Assets. The new method (SAVV+P) can then identify a series of positional vectors able to "move" from the initial SAVV classification to a vision of the territorial potentialities.

Positional vectors are defined through the calculation of two new cross-dimensional indexes Potential Asset Index (PAI) and Potential Trigger Index (PTI), as follows:

$$PAI_i = \sum_{j=1}^{n} wjYij \tag{1}$$

$$PTI_i = \sum_{k=1}^{m} wkFik \tag{2}$$

where wj and wk are the weight for each variable j and k (from 1 to n) and Yij or Fij represents each asset or trigger indicator. For each municipality/territory (i) PAI (x) and PTI (y) are then represented by position vectors in Phase 4. Since the order of magnitude and unit of each indicator is different, all the data must be standardized by applying the min-max standardization method, underling that, in case of potentials evaluation, only positive indicators are considered.

Phase 4. Position vectors can be classified in three different categories based on their magnitude:

- *Moving* (maximum): characterized by a high PAI value and a high PTI value;
- *Evolving* (medium): characterized by a high PAI value and a low PTI value or low PAI value and a high PTI value;
- *Starting* (minimum): characterized by a low AI value and a low TI value.

The SAVV+P classification of the potentialities is determined by position vectors that show - for each portion of the considered territory (i.e. municipality) - potential assets and triggers by using PAI and PTI as coordinates. As the values change, the position vector will change in length or in direction or in both length and direction. Positioning vectors must then be interrelated with the first classification deriving from SAVV, calculated for each territorial portion: so this "potential movement" can add a new vision, based on the recognised potentials (SAVV+P).

This procedure allows to identify territories which even starting from similar conditions, due to their own potential can change their situation in different ways.

3 Study Area and Data Sample

The proposed method was applied in one of the four contexts analysed in the "B4R - Branding4Resilience" research project (www.branding4resilience.it): the Alta Valsesia territory in the northern part of Piedmont, a mountain area including 17 municipalities (Alagna Valsesia, Alto Sermenza, Balmuccia, Boccioleto, Campertogno, Carcoforo, Cervatto, Cravagliana, Fobello, Mollia, Pila, Piode, Rassa, Rimella, Rossa, Scopa, Scopello) and numerous small hamlets (Fig. 2).



Fig. 2. The Alta Valsesia territory and the new SNAI Valsesia Area (Source: Authors' elaboration)

Excluding Alagna Valsesia, whose both population and tourism trends arose in the last few years, the socio-economic context of these areas is rather weak due to limited public essential services and an average population density very low (6,69 inhabitants per square kilometre). The progressive depopulation and aging, as well as a lack of homogeneity in tourist flows and the progressive abandonment of the built heritage, represent other key issues that highlight the vulnerability of this territory. By evaluating these critical conditions, in 2022 the Italian Ministry of Territorial Cohesion designated the Valsesia territory as one of the new "inner areas" of the second programming cycle of the Italian "National Strategy for Inner Areas" (SNAI). Currently, the Mountain Union of the Valsesia Municipalities is leading a decision process aimed to manage funding of more than 10 million Euro by identifying and selecting specific activities and actions to be funded and implemented to counteract the current negative trends and foster new economies and local development strategies. In this crucial process, it is important to strategically address this funding in the most vulnerable areas, which must be identified by considering both their current condition and their reactivation potentialities.

In this perspective, the knowledge base that Polito RU has structured since the beginning of the B4R project in 2020 constitutes an important starting point to be used and properly managed in order to support local authorities in defining their strategies.

Therefore, with the aim of supporting the Alta Valsesia local authorities and integrating the previous results achieved by means of the application of SAVV, 38 dichotomous indicators were collected and included in the knowledge base structured in a GIS (Table 1), to better explore and evaluate the territorial potential of the 17 considered municipalities. In particular, the following qualitative analyses conducted in the first two years of B4R project have been considered in this paper as sources of potential assets and triggers indicators: Stakeholder analysis, Survey on built heritage, SWOT analysis.

Table. 1. Data sample indicators and related sources (Source: Authors' elaboration)

Source	Numbers of indicators	Type of indicators	Indicators identification
Stakeholder analysis	6	Dichotomic	Stakeholders in Environment, Culture, Commercial, Sport, Tourism areas of interest
Survey on built heritage	7	Dichotomic	Buildings to be reused; religious buildings; building complexes (hamlets), footpaths and trails; rural buildings, eco-museums, municipal wash-houses
SWOT analysis	25	Dichotomic	Geopark; Natural park; Gran Traversata Valsesia (GTV); Gran Traversata Alpi (GTA); Sentiero Italia; Local public transport; Walser area; Art Nouveau and Eclectic Architecture; Historical bridges; Ski resorts; Ecosystem Services; Flexibus; Commercial Activities; Sacro Monte Varallo; Craftsmanship; Administrative Dynamism; Pro Loco; Regional call for funds; Interregional call for funds; National call for funds; Interreg project; SNAI; Valsesia Tourism Project; Walserweg Italia; Energy Community

The first, well-known methodology, the Mendelow (Power-Interest) stakeholder analysis was applied to understand each stakeholder role in relation to the 8 main objectives of the B4R research project [24]. More than 100 stakeholders were analysed and classified: most of them are institutions and third sector organizations, but there are also

some companies, local associations and museums [25]. The research group evaluated the power (in terms of power of action and change) and the interest of these stakeholders by applying the Mendelow power-interest matrix [21, 22]: this evaluation process highlighted four different stakeholder categories (key stakeholder, contextual stakeholders, subordinate stakeholders, marginal stakeholders) and improved the knowledge base related to the 17 considered municipalities. This important knowledge base fostered the organization of e series of meetings and interviews, which allowed the research group to better know and understand some issues, values and vulnerability aspect of the Alta Valsesia territory.

Some aspects related to the built heritage were investigated by means of a survey addressed to the Mayors of the considered Municipalities: each public administration was asked to report and describe different types of assets that potentially could be redeveloped in order to create new enhancement opportunities for the territory. The aim of this "bottom-up" exploration, conducted in the first months of 2021 and integrated in 2022 and 2023, was to identify different building typologies, both publicly or privately owned: single buildings, complexes of buildings, infrastructures, paths, production sites, civil constructions in general. The Polito B4R research group collected and processed the answers from the municipalities that participated to the survey, for a total of 41 assets or groups of assets reported. A meeting with each Mayor was then organized to deepen the knowledge and condition of the assets and to discuss about specific needs and possible redevelopment strategies. The outputs did not represent a systematic census of assets, but highlighted a rather heterogeneous list of different kinds of assets: buildings to be totally or partially reused, religious buildings (churches/chapels/oratories), groups of buildings (hamlets), paths and routes (pedestrian and cycle paths in different conditions of efficiency and maintenance), rural buildings, eco-museums, municipal washhouses [25]. Currently, some of these assets are still unused or in a state of decay, while others are going to be redeveloped by taking advantage of specific new funding measures. In fact, in the last few years, some financing opportunities emerged in Alta Valsesia, thanks to specific policies and public calls: in addition to the abovementioned SNAI opportunity, numerous funding chances derived from the National Recovery and Resilience Plan (PNRR), bank foundations and initiatives promoted by the local GAL "Terre del Sesia". Therefore, numerous projects were funded and activated in some of the considered municipalities, so their implementation is currently representing potential triggers for both heritage redevelopment and new economies fostering.

Lastly, two SWOT analyses were conducted in parallel focusing on B4R project and SNAI project, categorise data form different sources in the four class of strengths, weaknesses, opportunities and threat, and in different categories of analysis related to the 4 dimensions of the B4R project.

4 Results

Assuming the 38 new indicators created and structured in the knowledge base on the basis of the qualitative analyses conducted in the context of the B4R project and assumed as data sources, the two indexes PAI (Potential Asset Index) and PTI (Potential Trigger Index) were built and then transformed in 17 position vectors. Given their different

nature, the evaluation of PAI and PTI was made by using dichotomous variables for each municipality considered (Fig. 3).

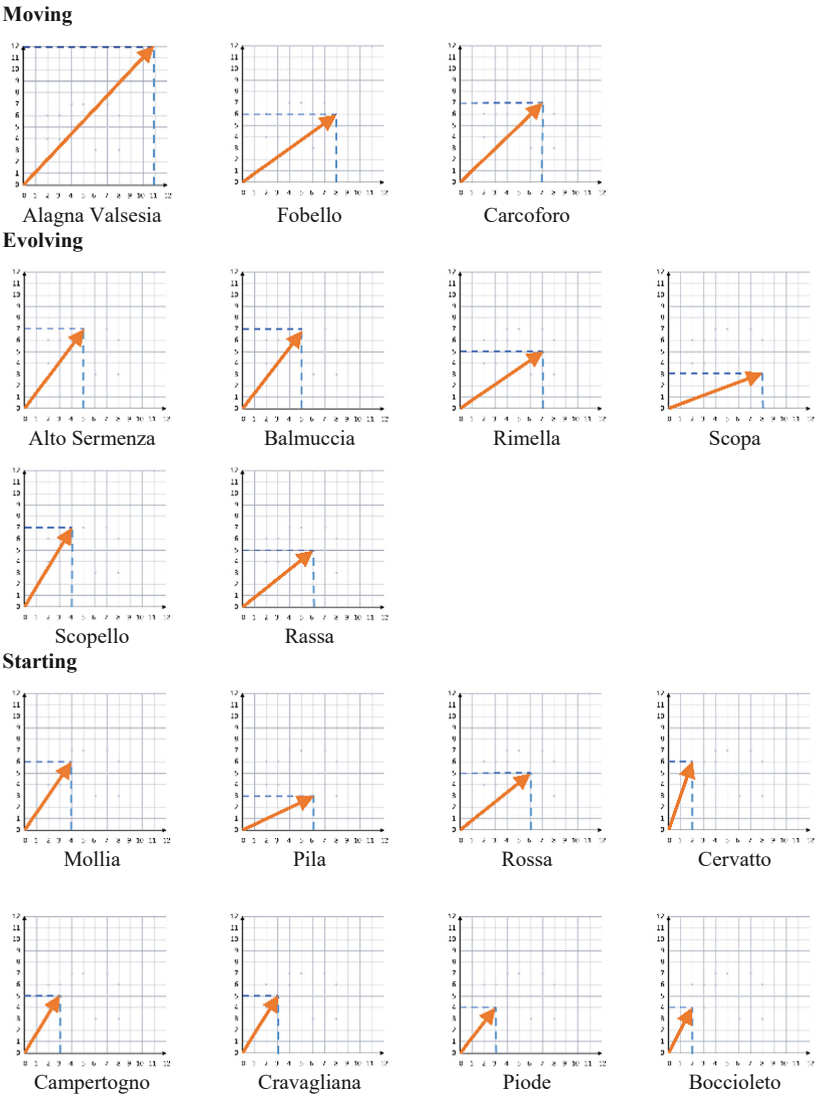

Fig. 3. Municipal potential position vectors with X = PAI and Y = PTI (Source: Authors' elaboration)

The 2 Municipalities with the higher score of potentialities (>= 10; Alagna, Scopello and Carcoforo) are *Moving*, i.e. they could implement numerous and different actions/interventions for the vibrancy and attractiveness of the area. The last 2 Municipality with the lowest score (<5) are Piode and Boccioleto, which demonstrate limited

potential for actions/interventions and activators. All the other Municipalities, having potentially moved, can be defined *Evolving* and *Starting* since they activated few actions and interventions to improve their status.

The inclination of the vectors indicates the different potential dynamism for each municipality, determined by the values of potential triggers and potential assets. Observing the results also from this point of view, it can be seen that Rimella and Scopa have greater opportunities for assets development, while in Scopello, Cervatto and Mollia there is a strong presence of active players.

Then, starting from SAVV results [20], Fig. 4 shows the 17 municipalities of the Alta Valsesia divided by their three valleys (Val Grande, Val Sermenza e Val Mastallone) that clearly highlights the differences of the three main Alta Valsesia areas.

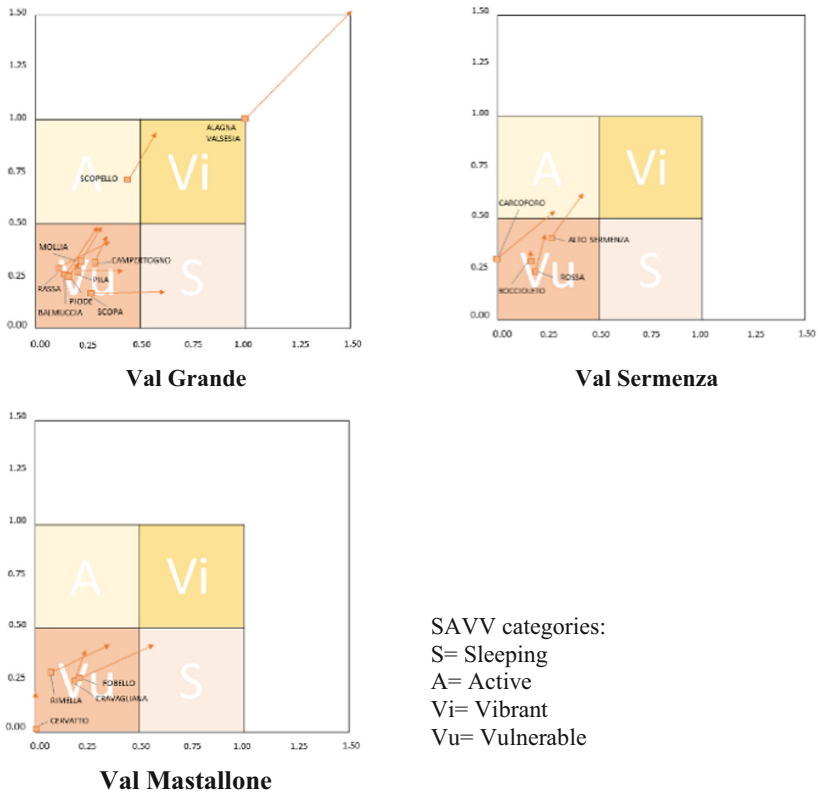

Fig. 4. The SAVV Territorial Matrix and Potential Asset and Trigger position vectors (Source: Authors' elaboration).

According to the SAVV evaluation method, Alta Valsesia can be defined a fragile territory, with a clear prevalence of Vulnerable municipalities (15 on 17), with the exception of Scopello (Active) and Alagna Valsesia (Vibrant). Alagna Valsesia is, in fact, a well-known tourist destination, located at the foot of Monte Rosa, which represents the main visitor's attraction in summer and in winter of the area. Both in Alagna and in

Scopello there are ski resorts and other tourist activities, as well as some services and accommodation facilities. The other municipalities, instead, have limited (or scarcely known) tourist attractions, and also their built heritage is often abandoned or in a bad state of conservation; in particular, Cervatto emerges as the most Vulnerable municipality.

Potentials position vectors could totally transform the initial SAVV classification. Alagna Valsesia constitutes a total outlier, strictly followed by Scopello; if their potentials are developed, they could become even more vibrant in comparison with other municipalities. This means that the gap between the strongest and the weakest areas will become even wider, causing a real dichotomy in the territory, if the potentialities are not considered as real driving forces/triggers also for the other municipalities. The local government (Unione Montana) should avoid this extremisation of territory by redistributing wealth and funds in a more equitable way across the territory. A surprising result is the potential vector of Carcoforo in Val Sermenza, which even starting from a very *Vulnerable* condition (few trigger but no assets) could become an *Active* municipality. In fact, it has some potentialities both in terms of assets (it owns many interesting buildings to be renovated and reused), and triggers, by proposing several events and activities in the territory.

Scopa is another municipality that, with the realization of its asset potential, could change its classification from *Vulnerable* to *Sleeper*: it presents, in fact, a lot of assets such as big building stock suitable to be reused, a network of religious chapel, rural buildings and the related networks of trails and paths, but very few trigger activities.

In Val Mastallone Fobello can became a *Sleeping* municipality because of its quite high potentials in assets and triggers.

In Val Sermenza, in addition to Carcoforo, also Alto Sermenza has many potentialities in terms of triggers that could allow it to overcome its vulnerability, becoming an *Active* municipality.

Lastly, it is worth mentioning the negative situation of Boccioleto and Piode, that would remain *Vulnerable* even with the implementation of their potentials, since they are unfortunately very limited both in triggers and assets. Also in this case, the local governments should intervene with the activation of specific policies to support these territories.

5 Conclusion

By assuming the SAVV evaluation method to explore fragile territories and identify the most vulnerable and vibrant areas within the considered territory, a new method (SAVV+P) was proposed to classify their potentials in 3 different categories: *Moving*, *Evolving* and *Starting*. Both SAVV and SAVV+P methods were tested in the Alta Valsesia area, which is one of the inner areas studied in the context of the "B4R -Branding4Resilience" research project. The analysis assumes the perspective of analysing the developing potential for new cultural-tourist infrastructures and the results showed how the considered municipalities could enhance their territories by defining and developing their potential assets and triggers. Results demonstrated how the integration between quantitative and qualitative research could effectively drive to different but complementary results. The municipalities of Alagna Valsesia and Scopello

present the highest potentialities to became even more *Vibrant*. Other municipalities (Scopello, Scopa, Alto Sermenza, Carcoforo and Fobello) could develop their potentialities and change their condition from *Vulnerable* to *Sleeping* or *Active*. Finally, some municipalities, such as Piode e Boccioleto, currently do not have sufficient strength and opportunities to change their condition of vulnerability.

Supporting the identification and development of new territorial opportunities and enhancement strategies is only the first step for the redevelopment of a territory; tailored territorial policies must be set up to guarantee equal opportunities for all territories, focusing on the less autonomous and more vulnerable ones. Moreover, above all, equally structured processes of management, observation and monitoring of the results must be identified, to be applied in the implementation phase of these strategies, to analyse the results of the actions, correct the directions and guarantee the effectiveness of the strategies, as recently carried out by some studies on the first cycle of intervention implementation in SNAI areas [26–31].

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A Stakeholder Analysis to Support Resilient Strategies in the Alta Valsesia Inner Area

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Abstract. In Italy, a growing attention has been paid for inner areas, which represent fragile socio-economic contexts characterized by a growing marginalization and progressive depopulation. In this paper a particular attention is focused on the necessity of identifying the role of different stakeholders in defining resilient strategies and measures to support the development and reactivation of these inner territories. This article proposes a stakeholder analysis and mapping developed in the context of the "B4R-Branding4Resilience" research project, in Alta Valsesia, which is a fragile territory that has recently become a part of an inner area according to the SNAI classification. The aim of this paper is to propose a stakeholder analysis and mapping to identify the key players with an active role in the enhancement of inner territories. In particular, a quantitative approach is applied to assess the potential role of each stakeholder and improve the power-interest matrix. Results show the presence of a large number of key stakeholders that change their position in relation to eight different challenges and to their related level of power and interest. This research on the one hand highlights the importance of the identification of key stakeholders in the definition of reactivation and enhancement strategies and on the other suggest the use of the stakeholder analysis as a tool to avoid conflicts during strategic processes.

Keywords: stakeholder analysis · inner areas · territorial enhancement · resilience · B4R research project

1 Introduction

In the last decades, the uncontrolled growth of large urban hubs has accelerated the impoverishment and depopulation of rural centers, despite their enormous natural and human capital [1]. In Italy, a growing attention has been paid in recent years to inner areas, which represent fragile socio-economic contexts to be reactivated by means of funding addressed to strategic policies and projects. The Italian National Strategy for Inner Areas (SNAI) was developed and implemented to counteract this weakening process and to support public administrations and local governments in defining concrete actions and

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strategies. With this aim it is important to study these particular contexts by means of data-driven analyses and experts involvement able to contrast treats and highlight strengths and opportunities [2–6].

In this paper particular attention is focused on the necessity of identifying the key actors to be involved to support resilient measures development in territories characterized by a growing marginalization and progressive depopulation. In this framework the stakeholder analysis represents an essential operational tool to identify and map the stakeholders as people able to influence the enhancement processes and to generate positive or negative impacts on the considered territory [7].

With these premises, this article proposes a stakeholder analysis and mapping to identify the key players with an active role in the enhancement of inner territories. In particular, assuming the well-known power-interest matrix [8], a quantitative approach is applied to assess the potential role of each stakeholder in relation to specific objectives and challenges.

The proposed methodological approach is applied to the inner territory of the Alta Valsesia in Piedmont (North of Italy), which a Research Unit of the Politecnico di Torino (Polito RU) assumed as case study in the context of the research project of national interest (PRIN) "*B4R - Branding4Resilience*" (www.branding4resilience.it, accessed on 4 April 2022) (Ferretti et al., 2022). The Alta Valsesia is also part of a wider territory, which has recently become an inner area according to the SNAI classification (Regional Council Resolution n. 28/5251 of 21 June 2022) This paper illustrates the process followed by the Polito RU in the application of the stakeholder analysis performed during the first year of the B4R research project [9], and highlights its current relevance in supporting public entities in the decision process that has been recently launched to define the SNAI strategy and the related projects to be funded.

The article is structured in four main sections. The methodological approach is presented in the first section, while the study area is described in the second section. The data sample and the results are illustrated respectively in the third and fourth section. Lastly, the conclusion focuses the discussion on the main results and presents further implementations.

2 Methodological Approach

This research focuses on the methodology for the stakeholder mapping proposed by Aubrey Mendelow [10]. In particular, the methodological approach is based on the Power-Interest assessment by Olander and Landin [8], which developed the original Power-Dynamism matrix into the Power-Interest matrix. The assumed methodology is proposed with some new operations (Fig. 1) to assess the role of each stakeholder more precisely by means of the use of numerical scores. Four phases are proposed, which guide a flexible application of this classical methodology to be adapted in different study areas, by requiring amendments and implementations to better represent the field of expertise and the role of specific actors.

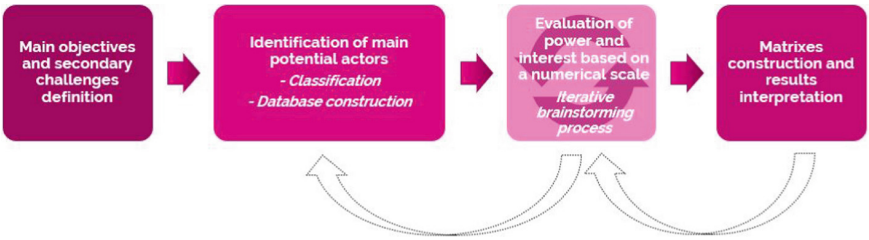


Fig. 1. Flowchart of the methodological approach (Source: Authors' elaboration)

2.1 Main Objective and Secondary Challenges Definition

The research's main objective and some secondary challenges must be defined at the beginning of the analysis to identify the correct domain of actors to be classified and eventually involved in subsequent enhancement processes. In particular, an excellent method to define the main objective and challenges is to apply the well-known S.M.A.R.T. criteria [11] to avoid possible errors caused by non-specific and insufficiently explicit objectives. S.M.A.R.T. criteria are intended as guidelines to help the management of the challenges and their realization. According to these criteria, the objective of the research and the secondary challenges must be [11]:

- Specific: target a specific area of action;
- Measurable: quantify or at least suggest an indicator of progress;
- Assignable: specify who will do it;
- Realistic: based on available resources (material and human);
- Time-related: with a specific deadline when the results can be achieved.

It is important to notice that the main objective or the challenges must not necessarily fit each criterion, but the more the challenge adheres to the points, the smarter will be.

2.2 Identification of the Main Stakeholders

Starting from each defined challenge, it is crucial to identify the main stakeholders and potential actors that can be involved in possible enhancement processes. Each stakeholder is classified in a structured database and associated with a unique ID necessary for the subsequent analysis. In this phase, it is important to list and classify the main public and private subjects by considering both their location and their territorial competence (territorial level), their areas of competencies, their juridical forms and reference sectors (Fig. 2).

In order to better identify and classify the main stakeholders and avoid errors, it is crucial to define the areas of competence that must cover all the possible competencies and fields of interest of the research. In particular, the present methodological approach considers different areas of action of the possible actors to intercept all the economic sectors and activities.

The classification process and the identification of the category for each stakeholder (intended as the legal identity of the stakeholder) are crucial to understand how to manage the cooperation for each challenge. This methodology proposes six categories, with

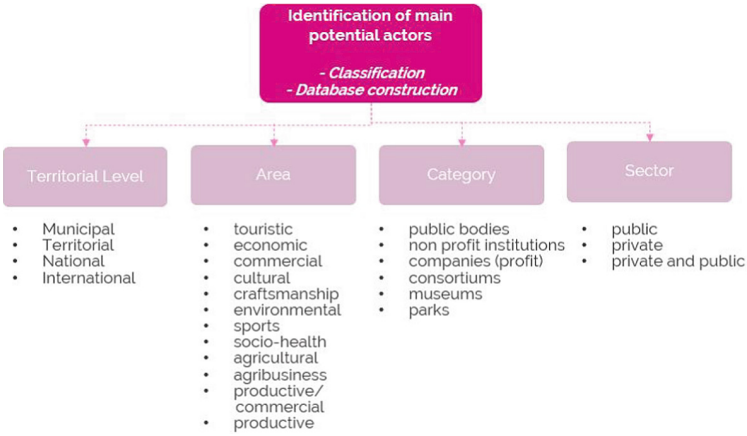


Fig. 2. Identification and classification of the stakeholders. (Source: Authors' elaboration)

particular attention to some specific entities (like museums and parks) that are essential features for inner areas. Public bodies are intended as administrations and other types of government entities both at the local and territorial levels; non-profit associations include voluntary organizations, social promotion associations, philanthropic entities, social enterprises, including social cooperatives, association networks, associations, recognised or unrecognised, and foundations.

2.3 Evaluation of the Stakeholders' Power and Interest Based on a Numerical Scale

Assuming the research's main objective and the defined secondary challenges, it is fundamental to evaluate the power and the interest of the previously identified stakeholders in order to set up the power-interest matrix. The actual levels of stakeholders' interest and power properly reflect the corporate governance framework within which the organization operates.

In order to better specify the methodology assumed and developed in this paper [7], it is important to clarify what is intended for:

- *Power*: the ability to influence strategies or project resources or whether stakeholders have the potential to do;
- *Interest*: how interested they are in the organization or project succeeding or what are the stakeholders' expectations on the purposed strategies;

The proposed quantitative approach is aimed to assess the potential role of each stakeholder by means of the use of numerical scores: this means that the power and interest levels are assessed, assuming a predefined numerical scale. Nevertheless, it is important that the final assessment is made by a group of experts participating in an iterative brainstorming process aimed to reduce subjectivity present in individual assessments.

Each expert should consider the roles and past initiatives of the stakeholder to prevent preconceived assumptions. The roles of stakeholders change in relation to the challenge considered for the analysis; so even if a stakeholder is excluded for a specific challenge due to its null power or interest, it is necessary to reconsider it in relation to the other challenges. The scores identified by the group of experts provide the coordinates for the construction of the power-interest matrixes.

2.4 Matrixes Construction and Results Interpretation

The assessment of stakeholder power and interest levels based on a numerical scale establishes their positions within a double-input matrix: the level of power on the y-axis and the level of interest on the x-axis.

The four quadrants in Fig. 3 identify the following different roles and potential partnerships levels of the considered stakeholders [7]:

- the key stakeholders (KS) or the promoters (high power and high interest);
- the contextual stakeholders (CS) or the latents (high power, low interest);
- the subordinate stakeholders (SS) or the defenders (low power, high interest);
- the marginal stakeholders (MS) or the apathetics (power and low interest).

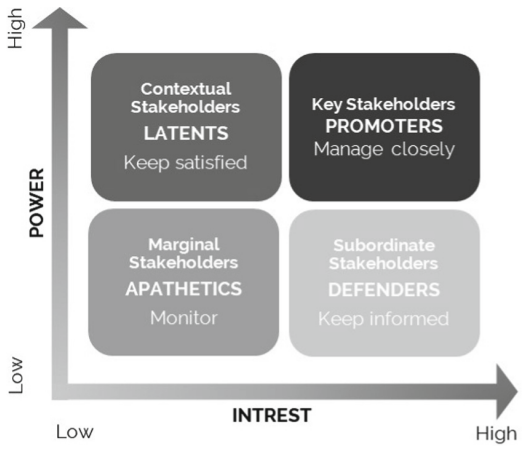


Fig. 3. Stakeholder analysis and mapping based on the power/interest matrix (Source: Author's elaboration on (Mendelow, 1981)

3 Study Area and Data Sample

The study area (Alta Valsesia) is the focus area of Polito RU of B4R project since 2020, and it was included in the SNAI inner area "Valsesia" since 2022. It is an alpine area in the northern part of the province of Vercelli (Piedmont), which takes its name from the Sesia river.

The territory of Alta Valsesia includes 17 Municipalities (Alagna Valsesia, Alto Sermenza, Balmuccia, Boccioleto, Campertogno, Carcoforo, Cervatto, Cravagliana, Fobello, Mollia, Pila, Piode, Rassa, Rimella, Rossa, Scopa, Scopello) as shown in Fig. 4.

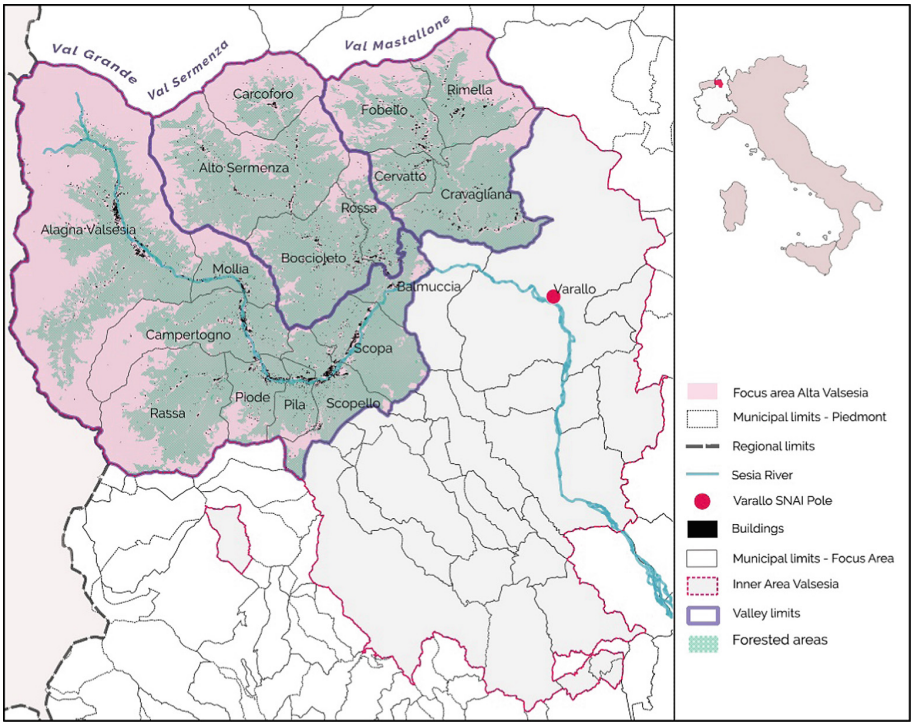


Fig. 4. Territorial framework of the analysis (Source: Authors' elaboration).

The main valley is the Val Grande and extends from Monte Rosa up to Varallo Sesia, classified by SNAI as a "Pole" due to the number of inhabitants (about 7,000) and the presence of commercial activities and some most relevant schools and essential citizenship services. Numerous side valleys take their name from the streams that flow into the Sesia river: on the left orographic side, Val Mastallone and Val Sermenza; on the right side, Val Sorba, Valle Artogna, Val Vogna and Val d'Otro. The Alta Valsesia is considered "the greenest valley in Italy" thanks to the rainy weather that characterize the valley: the great nature capital is evident considering that Alta Valsesia is located within the UNESCO area of the Sesia Val Grande Geopark, which also includes the Alta Val Sesia and Alta Val Strona Natural Park.

During the first year of the B4R project, contextually with territorial data analyses and mapping [12, 13], the Polito RU analysed the stakeholders of the Alta Valsesia territory: once an initial list of stakeholders was drawn up, a structured database was built and progressively increased on the basis of the information gathered during a series of surveys and interviews carried out in parallel with other territorial analyses. Table 1 shows the data structure of the main variables included in the database.

Table 1. Data structure of the main variables (Source: Authors' elaboration).

Data structure	Data content	Data value	
Variable name	Short description	Vocabulary	Levels
Territorial localization	physical localization of the headquarters of the stakeholder	closed	international, national, territorial, local
Level of competence	territorial area within which it is possible to detect the effects of each stakeholder's actions	closed	international, national, territorial, local
Legal identity	legal form assumed by the stakeholder according to the Italian legislative framework	closed	companies, no profit organizations (NGO), public entities, museums, parks
Area of interest	identification of the principal area in which the stakeholder operates	closed	touristic, economic, commercial, cultural, craftsmanship, environmental, sports, socio-health, agricultural, agribusiness, productive/commercial, productive
Sector	identification of the sector in which the stakeholder operates	closed	public, private

The final data sample included 105 stakeholders with a possible role for the resilient development of the territory and its communities. Each municipality was considered during the analysis by taking into account the role of each local administration as a potential actor and by considering the entire area as a system of multiple actors that collaborate together to achieve different goals.

During these exploratory analyses of the territory, the knowledge of the stakeholders and the direct contact with some of them allowed the Polito RU to identify and map the main stakeholders, as well as to highlight peculiarities, values and fragilities of Alta Valsesia. The research activities developed in the study area by the Polito RU supported the identification of the main stakeholders of the territory and their classification brought out their role.

4 Results

During the first year of the B4R research project, all the four Research Units developed a stakeholder analysis and mapping based on the power/interest matrix (Mendelow 1981): the main objective and the secondary challenges were jointly defined and then each RU adapted it to its context and also applied specific operations to assess the role of each stakeholder. Polito RU applied the aforementioned methodological approach to the Alta Valsesia territory to identify the main stakeholders and actors to determine the main potential actors to be involved enhancement processes to reactivate the territory.

4.1 Main Objectives and Secondary Challenges Definition

The stakeholders analysis presented in this research assumed the main research framework of the B4R project and the main objective to define strategies for a resilient development of inner territories and their communities. Then B4R research group preliminarily defined also eight secondary challenge, as a reflection of specific outcomes to be achieved (Fig. 5). (Ferretti et al. 2022)

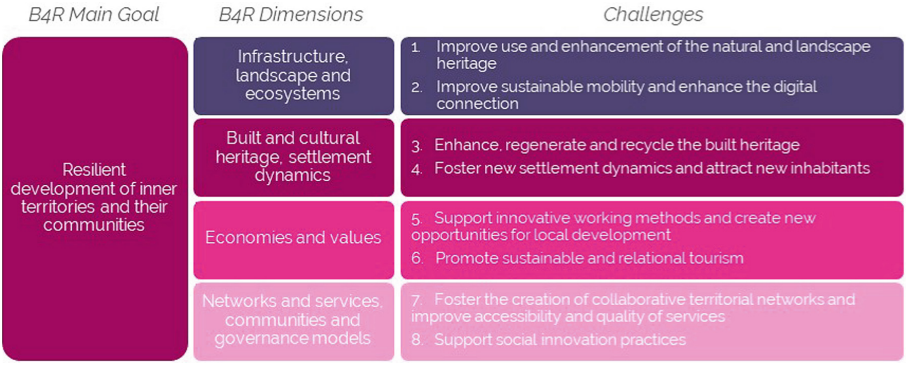


Fig. 5. The B4R main objective and eight secondary challenges. (Source: Authors' elaboration on Ferretti et al. 2022).

In particular, the eight challenges were classified in the four dimensions used during the first year of B4R project in parallel with exploratory data analyses and mapping[14]:

- Dimension 1: Infrastructure, landscape and ecosystems;
- Dimension 2: Built and cultural heritage, settlement dynamics;
- Dimension 3: Economies and values;
- Dimension 4: Networks and services, communities and governance models.

The eight challenge refers to different analysis topics [14]: Dimension 1 is mostly related to the natural capital and the development of technological and telecommunication networks, whereas the Dimension 2 deals with material and immaterial heritage and the types of settlements. Dimension 3, instead, explores the economic context and dynamism by analyzing the main economic sectors and the real estate market, while Dimension 4 refers to policy and planning tools with a special attention to key actors and communities.

4.2 Identification of the Main Stakeholders

The Polito RU identified and classified 105 stakeholders: most of them are public entities (37%) and non profit organizations (32%); furthermore, in line with the main objective of economic and tourist enhancement of inner territory, companies (19%) and private or public museums (10%) were identified as possible actors to be involved in future enhancement processes (Fig. 6).

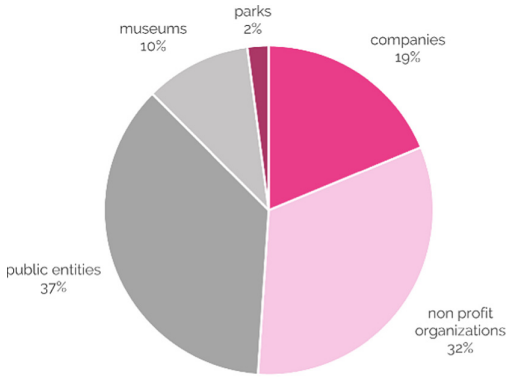


Fig. 6. Classification of the stakeholder legal identity. (Source: Authors' elaboration).

Results showed in Fig. 6 underlined the public and non-profit character of most of the stakeholders in Alta Valsesia (81%), prevalent than the profit sector (19%).

Among the public entities, all 17 municipal administrations of Alta Valsesia and all second-level bodies involved in the coordination between municipalities were identified. These include the Unione Montana dei Comuni della Valsesia, which is responsible for planning the socio-economic development of the area, managing the associated services and defining unitary strategies and actions. Another important institution is the Local Action Group (GAL) Terre del Sesia, constituted as a consortium company with mixed public-private participation that supports rural development projects through the enhancement of local traditions and culture, typical products, and traditional agricultural and craft activities.

Among the non-profit organisations of social utility (NGO) it is important to cite the Fondazione Valsesia Onlus, which was established with the aim of facilitating collaborative networks, social planning and active citizenship. Some NGO are aimed to support people in physical and social disadvantage: this highlights the presence of collaborative networks at the citizens level; in particular, the Social Cooperative "Il Bucaneve" pursues the objective to help disadvantaged people in the job hunting. Lastly, among the associations related to the economic area there is "Spazi Comuni", which offers free wi-fi stations in the municipalities of Alto Sermenza, Carcoforo, Fobello, Rassa, Rossa and Varallo, thus offering a new service for citizens and smartworkers.Among the companies there are groups such as the CAI (Varallo section of Italian Alpine Club), which has been active in the area since 1867, and some companies connected with the management of strategic activities and facilities for mountain tourism, such as the company Monterosa 2000 S.p.A. and Rifugi Monterosa MBG srl. Companies related to river sports were also identified as relevant in the mapping: among these are the Centro Canoa Rafting Monrosa (Balmuccia), Sesia Rafting (Vocca) and Centro Rafting & Canyoning Valsesia Sport (Scopello).

Considering the category of museums, 10 stakeholders were identified, including the Pinacoteca di Varallo and the Museo Walser di Pedemonte (Alagna Valsesia) and the Ecomuseo della Valsesia, with several points of attraction spread throughout the territory. Parks also play an important role despite their low percentage (2%) due to the

low number of legal identities; among them there is the UNESCO area of the Sesia Val Grande Geopark, which also includes the Alta Valsesia and Alta Val Strona Natural Park.

Results of preliminary descriptive analyses show the area of interest of the identified stakeholders and highlight the relevance of the economic and touristic field, as well as the tourism industry as the driving force for this territory (Fig. 7).

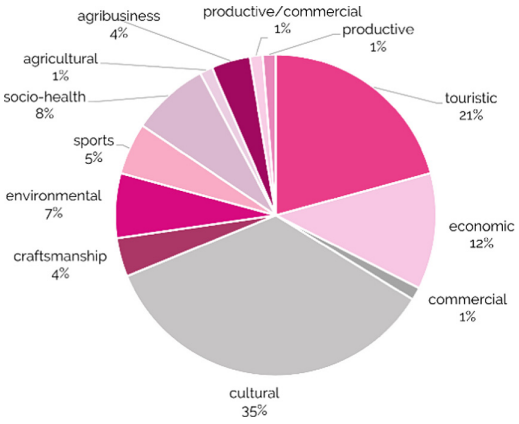


Fig. 7. Classification of the area of interst. (Source: Author's elaboration).

Results show also that there is a considerable percentage of stakeholders operating in the cultural field (35%) and in the tourism sector (21%), while only a little group operate in the commercial, productive and agricultural sectors (1%).

In the cultural area, some important associations specifically promote the knowledge and dissemination of the Walser culture and their lands (Folk Group Die Walser Im Land, Walser Gruppe Rima S. Giuseppe and the Cultural Association Walser Presmell in Valle Vogna).

In relation to the tourism sector (21%) an important stakeholder is the Local Tourist Reception and Promotion Agency of Vercelli and Valsesia (ATL) which disseminates tourist information related to the territory and provides communication campaigns on the tourist offer. An active role for tourism is also played at the municipal level by the Pro Locos which organise entertainment activities for the population and tourists.

In the economic area (12%) there are some institutions that promote initiatives and activities for companies like the Confindustria Novara Vercelli Valsesia, which promotes the development of production activities through the representation of common interests, and the Young Entrepreneurs Novara Vercelli Valsesia, which launches initiatives to promote the inclusion of new entrepreneurs in the life of the association, in line with the aims of the national movement of Young Entrepreneurs of Confindustria.

For the environmental area (7%) is noteworthy to mention the Monterosa Foreste Association, which coordinates and supports forestry policies by promoting the sustainable use of agro-sylvo-pastoral resources, and the Società Valsesiana Pescatori Sportivi, which currently holds a concession from the Province of Vercelli for around 300 km of water (Sesia and tributaries) and traditionally deals with the reproduction of native fish

(at risk of extinction, such as the marble trout and the grayling) and the protection of the river environment. On the other hand, in the area of craftmanship (4%) it is important to mention the Artificial Marble Association of Rima S. Giuseppe which promotes local crafts, proposing to revitalise the artificial marble technique by building up a group of highly qualified and professional craftsmen to actively participate in professional and commercial initiatives, in cooperation with other public and private bodies active in the Valsesia area.

Lastly, the preliminary descriptive analyses show also interesting results concerning the territorial localization and the level of competence of the stakeholders (Fig. 8).

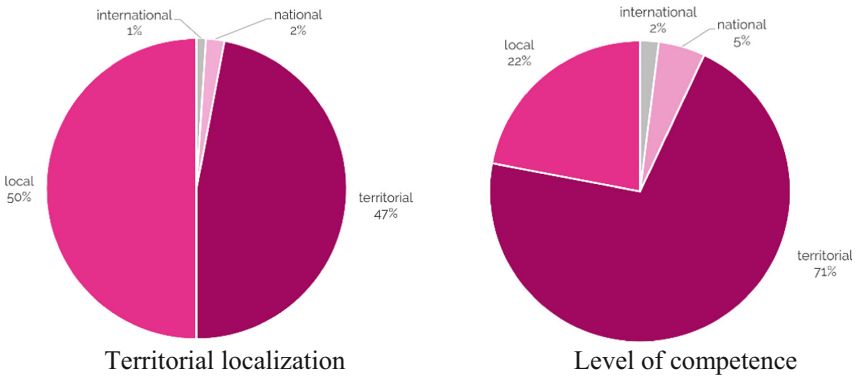


Fig. 8. Classification of the area field. (Source: Author's elaboration).

Fifty percent of the identified stakeholders operate at a local level, although it is important to emphasize that the range of action of these bodies dealing with the protection of the territory and valley settlements is often not only municipal but instead creates important repercussions at a supra-local level. Only small percentages (1–2%), on the other hand, refer to entities operating at national and international levels: among these, a prominent role is played by the Agency for Territorial Cooperation with the National Strategy for Inner Areas (SNAI). By considering the level of competence, a huge group of stakeholders operates at the territorial level (71%) highlighting a range of impacts that exceeds the limits of the study area; lastly, in relation to the international level of competence it is noteworthy to mention the cultural association "Presmell" that promotes the Walser culture and legacy.

4.3 Evaluation of the Stakeholders' Power and Interest Based on a Numerical Scale

The evaluation process was based on the proposed quantitative approach aimed to assess the potential role of each stakeholder by means of the use of numerical scores: to this aim the Polito RU assessed the power and interest levels for each identified stakeholder, by assuming a predefined numerical scale. In line with the methodological approach the best way to avoid errors was to discuss each assessment among the members of the

RU: therefore, numerous meetings and brainstorming sessions were organized in order to assess the power and the interest of each stakeholder and potential actor by sharing information and points of view.

The Polito RU decided to use a 4-level scale to evaluate the power and interest of the stakeholders with these specific ranges:

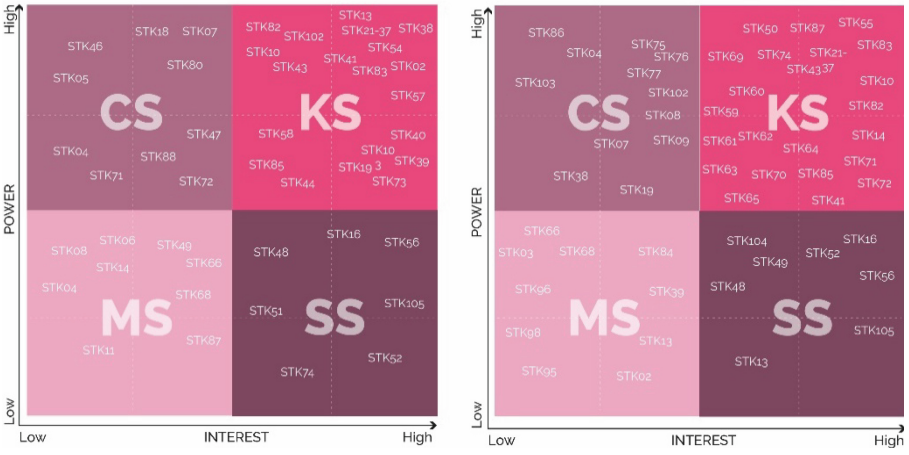
- 1 – low power/interest;
- 2 – medium-low power/interest;
- 3 – medium-high power/interest;
- 4 – high power/interest.

It is important to underline that each stakeholder was analysed in relation to each of the 8 abovementioned challenges; therefore, each stakeholder could present a different assessmnet for each of them, both in term of interest and power level.

After the construction of the eight matrixes, another discussion among the members of the RU was opened in order to eventually refine the assessments and to correctly interpret results.

4.4 Matrixes Construction and Results Interpretation

The stakeholder mapping constitutes the last phase of the proposed methodology: 8 different power-interest matrices were elaborated, one for each identified challenge. Two matrixes, based on the challenges defined for Dimension 3 "Economies and Values" are presented below as an example of the total elaborations (Fig. 8).



(a) Challenge n. 5: Support innovative working methods and create new opportunities for local development

(b) Challenge n. 6: Promote sustainable and relational tourism

Fig. 9. Examples of power-interst matrixes. (Source: Author's elaboration).

The matrixes presented in Fig. 9a individuate 21 Key Stakeholders (KS) that are mostly public bodies and associations: the Unione Montana dei Comuni della Valsesia

(Mountain Union of the Municipalities of Valsesia) (STK83) and the local administrations (STK from 21to 37) promote numerous initiatives aimed at the creation of new opportunities for local development. Another key stakeholder for this challenge is the Confindustria and the Gruppo Giovani Imprenditori (Young Entrepreneurs Group) of Vercelli (STK57) together with the Confederazione Italiana Agricoltori (Italian Confederation of Farmers) of Novara and Vercelli (STK40) and the Confederazione Nazionale dell'Artigianato (CNA) Piemonte Nord (STK39); these actors have both the power and the interest in elaborating shared strategies for the development of local economies and results can be achieved only if these organizations collaborate together and support local actors in managing strategies.

For the promotion of sustainable tourism Fig. 9b, presents 25 Key Stakeholders (KS) among which the Agenzia di Promozione Turistica Locale (ATL) Valsesia Vercelli (STK10), which plays the role of coordinator of all other touristic subjects, such as the Consorzio degli Operatori Turistici della Valsesia (Visit Monterosa) (STK43), the Capanna Osservatorio Regina Margherita (STK14) and the Google Local Guides (STK55). All the museums active in Alta Valsesia (STK from 59 to 70) and all the cultural and sports associations (context stakeholders) could contribute, albeit with a more circumscribed power, to the creation of a stronger experiential and relational offer for tourists.

Both matrixes individuate the Contextual Stakeholders (CS), most of which are private associations (STK71-72) and organizations at territorial or international level that are not so related to specific projects in the Valsesia Area. The Subordinate Stakeholders (SS) the Marginal Stakeholders (MS) constitute the smallest group of stakeholders because they have the lowest power for these two goals: in these quadrants it is possible to find little associations and actors at the local and municipal level that could not change the strategies but they can only support key actors during the process.

5 Conclusions

The stakeholder analysis illustrated in this paper supported the B4R Polito RU in understanding the interests and power of the main stakeholders that could play a role in possible enhancement processes in the Alta Valsesia area [7].

The four-phase methodological approach is based on the Power-Interest matrix and proposes some new operations to more precisely assess the role of each stakeholder by means of the use of numerical scores.

Transforming the methodological approach from a well-known qualitative evaluation to a quantitative- score-based evaluation opens new possibilities and makes the results more unbiased. In this application, 105 stakeholders of different fields and thematic areas were analysed and eight challenges were assumed as references to evaluate the interest and the power of the selected stakeholders in the perspective of developing new touristic and cultural enhancement strategies for inner territories [15].

The effectiveness of this new methodological approach is evident in relation to the outcomes and results that show how each stakeholder group can be interested in relation to the different aims of the project and therefore support the choice of specific strategies. At the same time, results show whether stakeholders have the power to make changes in the territory and how big the impact of their actions could be.

Results of this stakeholders analysis could be a useful tool to support decisional processes and strategies by selecting key stakeholders that must be involved during participatory tables, focus groups and other specific dialogues with the local actors for the Alta Valsesia area development. The stakeholders mapping – as a quantitative analysis - could be the basis for identifying potential actors in enhancement processes, such as the ongoing decision process that currently involves local actors and public administrations for the definition of the SNAI strategy. At the same time, the identification and classification of each potential actor could support the identification of possible new networks and relations between actors but also the understanding of existing disputes or conflicts that may affect the strategies efficacy. Stakeholders mapping could also help to avoid forgetting some key players in the area, risking creating new obstacles and problems for the development of each challenge by not involving someone in the processes.

Moreover, it is worth noting that different kind of power [7] exist such as: possession of knowledge, control of the environment or formal power, this level of specificity could be added to the mapping in further research by improving matrixes with a third dimension of analysis. At the same time, it is important to remember that important stakeholders at the territorial level (financial institutions, customers, suppliers, shareholders and unions) may belong to more than one stakeholder group and they group differently according to the main objectives and goals.

In this regard, further developments of the proposed methodology could include the integration of other stakeholders mapping methods (i.e. Venn diagram) in order to also understand the connections and links (existing and potential) between the stakeholders. Furthermore, the different evaluation of each potential actor could also be georeferenced and represented in cartography to highlight any spatial clusters and territorial thematic hubs.

The main spillover of this research is to use the stakeholder analysis as an important preliminary tool to manage participatory enhancement processes with discussion tables, and the involvement of the actors, with the aim of overcoming the existing local conflicts, applying objective methodologies and considering, with more awareness, the different political influences and interests of the main stakeholders. For example, this research could have a little but relevant impact for the SNAI programming, in the context of which this approach could be applied and tested.

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Emerging Trends in the Territorial and Rural Vulnerability-Vibrancy Evaluation. A Bibliometric Analysis

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Abstract. The very strong and fast process of industrialisation and urbanisation over the last century has impacted strongly the rural space, leading to its decline and progressive abandonment. This phenomenon has a strong influence on the socio-economic structure of the rural areas and as a consequence is provoking a lot of challenges connected to the future development of these territories.

In the last years, it has started an extensive research activity on the topic of the assessment of the state of the rural territories, approaching the given problem with the aim to be able to better understand and counteract it. As observed, this research activity can have an origin from a lot of different phenomena, gravitating in between terms such as the territorial vulnerability, fragility, marginality, peripherisation, resilience, socio-economic sustainability, vitality and vibrancy.

The main research objective of the present paper is to examine the emerging research fields and gaps of the quantitative indicator-based approaches for the territorial and rural vulnerability-vibrancy evaluation in non-urban contexts. This study was performed through the adaptation of a bibliometric analysis, more specifically authors' keywords co-occurrence analysis, which is a very useful technique for the assessment of the research topic distribution and future research frontiers. As a result, emerged that the vulnerability and the peripherisation are more consolidated topics, the vitality appears as a recent emerging field of study, while the territorial vibrancy as an interesting research gap that could become more investigated in the future years.

Keywords: vitality assessment · territorial vibrancy · fragile areas

1 Introduction

The fast industrialisation and urbanisation processes during the last century have led to rural decline characterised by high levels and still increasing unemployment, depopulation, economic depression and decrease in the quality of life in the rural areas [1].

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Anyway, the trend of urbanisation that the world has been experiencing is very likely to continue. According to the UNs medium fertility scenario, is estimated that the global population will grow from 7,6 billion people (total in the world) in 2018 up to 9,8 billion in 2050, from which around 68,4% is expected to be living in urban areas [2]. As a result, it can be expected the problem of the rural decline to become even more intensified.

Over the years, it has been made an effort to support and try to stimulate the development of the rural areas through some initiatives regarding the agricultural sectors [3], the diversification of the economy by promoting new forest products [4], the tourism [5] or the production of renewable energy [6]. Even though, some rural areas continue to face a lot of problems and to struggle to maintain their living conditions, often strongly influenced by the combination of population loss and population ageing [7]. Some other challenges that these rural areas are continuing to face are the poor access to essential public services, mobility problems, lack of employment opportunities, specifically in regards of the women and young people [1].

With the objective to counteract this global and very important problem, a lot of scholars have started researching quantitative methodologies for evaluation of the socio-economic conditions of the rural territories with the aim of being able to better understand the specific needs, threats and opportunities of a given territory [8]. As it emerges from some studies [9, 10], it is present a higher attention to the socio-economic problematics in urban contexts than in the rural ones [11] and a certain duality of the aspects from which the quantitative evaluation research of a territory can starts from. There are series of studies which base their evaluation on terms such as vulnerability [12], fragility [13], marginality [14], peripherisation [15, 16], all phenomena which carry an evident negative meaning. Still, there are others that have been approaching the same evaluation objective but from a different perspective, starting their research from positively meaning terms such as – resilience [17], sustainability [18], vitality [19], vibrancy [9, 10]. As it seems, some of these sub-fields of study have been more developed in the last years, while others still haven't reached their full potential of investigation [9, 10]. Still, it is important to mention that whatever of the terms the studies are being referred to, it is mainly studied the socio-economic aspect of the relative phenomenon. Nevertheless, a clear framework summarising the use and the relevance of these terms and related research topics has never been developed, at least at our knowledge.

The main research objective of the present proceeding paper is to examine the emerging research fields and gaps of the quantitative indicator-based approaches for the territorial and rural vulnerability-vibrancy evaluation in non-urban context.

In order to do that a bibliometric analysis is being performed, which is "a popular and rigorous method for exploring and analysing large volumes of scientific data" [20] and it is gaining more importance thanks to its utility to handle large amount of data and produce high research impact [20]. To support these analyses, in the last years a lot of bibliometric softwares have been developed such as Bib Excel, Ucinet, SCIMAT, VOSviewer and CiteSpace [21]. More specifically in this study the VOSviewer software (version 1.6.18) will be used, given its functionality to handle large amount of data and also visualise the outputs.

2 Methodological Approach

The methodological approach consists of 3 main processes, each of which can be divided in sub-steps, called phases. The process can clearly be observed in Fig. 1 and could also be applied for other bibliometric researches.

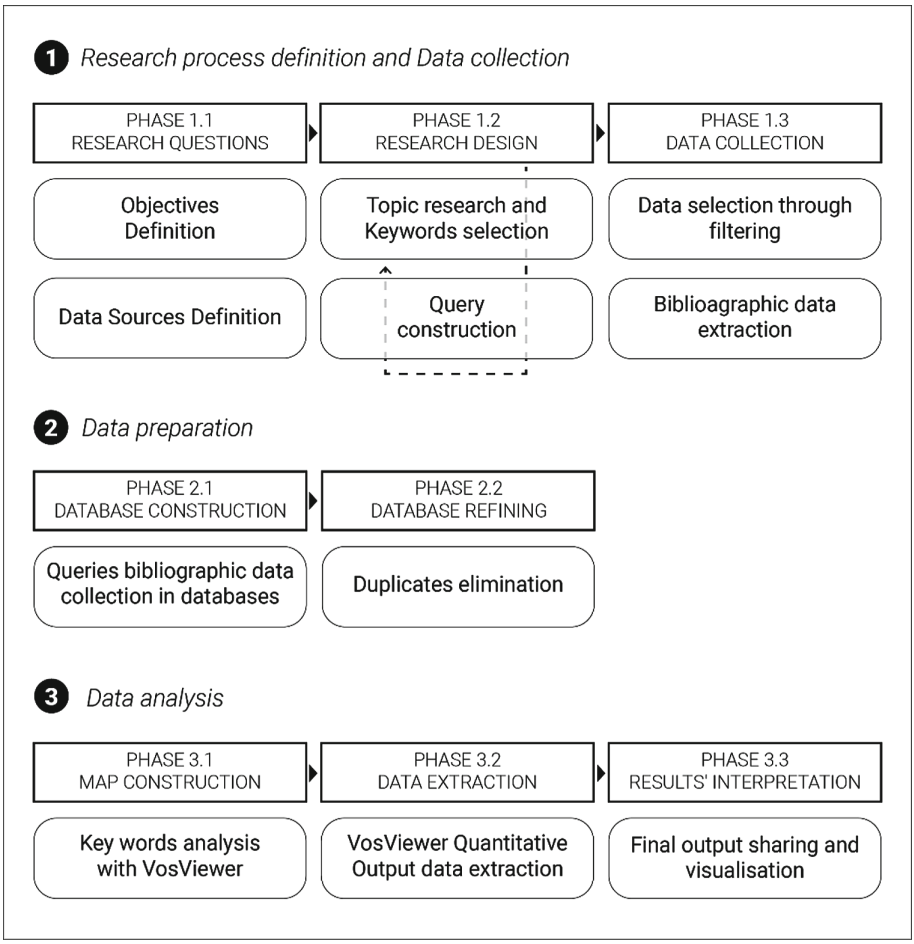

Fig. 1. Scheme of the methodological approach, showing its 3 main processes and related phases (Source: Authors' elaboration).

Research Process Definition and Data Collection. The first process of the methodological approach consists in defining the objective of the research and the main data sources to be analysed.

A critical point in the process is the identification of the keywords to be used for the construction of the research queries. Preliminary research of the topic can be done in order to better understand the state of the field of study, the main studied questions and

which are the appropriate keywords to be selected. Afterwards, the search queries are being constructed.

All queries are being applied in the chosen database and subsequently the results of each have to be refined through the engine criteria of limitation and/or exclusion. Thereafter, the bibliographic data of the final refined research results is being extracted.

Data Preparation. After all the separate bibliographic datasets (equivalent to the obtained results from every refined research query) are being downloaded from the chosen data source, they have to be merged in the final databases that would be subsequently used for the analysis.

The next phase consists in eliminating the duplicates of the records in each database created, an important operation that would allow to obtain valid and uncompromised results in the end of the whole process. With the completion of this phase, the databases could be considered ready to be used for the analysis.

Data Analysis. For the keyword analysis, the software VOSviewer is being used, which is a software tool for constructing and visualizing bibliometric networks, developed by the Centre for Science and Technology Studies of the Leiden University, The Netherlands. This analysis would allow to understand the main trends and gaps in the studied topic by visualising and obtaining quantitative information about the number of occurrences of the keywords, their links, the total link strength and their time relevancy according to the average year of publication.

After the definition of the combination of the most appropriate VOSviewer settings to be applied, two maps for each Database can be processed – one visualising the clusters of keywords, the number of the occurrences of the keywords and the links between them (in Network visualisation, with the Occurrences as a visualisation weight), the second visualising again the number of occurrences and the links but also the average year of publication of each keyword (in Overlay visualisation, with the Occurrences as visualisation weight and Average publication year as visualisation score).

Instead, for obtaining the quantitative information of the authors' keywords present in the Databases, it is possible to apply the same or different combination of the VOSviewer settings, basing the decision on the specific research objectives, and as a result two files can be extracted – a Map file and a Network file. The Map file contains information about the Clusters, the Links (the number of the links that a keyword has), the Total link strength (indicating the number of publications in which two keywords occur together [22]), the number of Occurrences, the Average publication year, the Average citations, the Average normalised citations of each keyword. Instead, the Network file contains information about the strength of the links between pairs of keywords. These two files can be connected in one unique one that allows to read correctly the whole information.

This dual process of analysis, gives the opportunity to obtain legible visual maps from the first process and a complete database containing all the information about the authors' keywords, from the second one.

Reading the outputs correctly is of a crucial importance. For the maps in the network visualisation, the circle size represents the number of occurrences of the keyword, the distance between two keywords - the relative strength and topic similarity, the colour of circles - the cluster of belonging [22]. In the overlay visualisation, the circle size again represents the number of occurrences of the keyword, instead the colour - the

average publication year according to the colour scale on the bottom right corner of the map. Analysing the VOSviewer Map and Network files is quite immediate. To read the Network file, it is important to link it correctly with the Map file. The last sub-step of the whole process is the critical analysis of the obtained outputs.

3 Results

Research Process Definition and Data Collection. The research objective in this case, as already mentioned above, is the examination of the main emerging research fields and gaps of the quantitative indicator-based approaches for the territorial and rural vulnerability-vibrancy evaluation in non-urban context and as a main data source the Scopus database was selected.

After brief research on a world-wide level, it was confirmed the duality of the research topic, and indeed that for the evaluation of the state of a given territory two perspectives of study exist – one starting from a negative presumption (the territorial vulnerability and fragility) and the other one levitating towards the positive (the territorial vitality and vibrancy) [8, 9]. Given this feature of the research topic, it was made a selection of key words representing both its negative and the positive aspect. The keywords representing the negative one are as follow: *fragility*, *marginality*, *vulnerability* and *peripherisation.* Instead, the ones representing the positive aspect: *vitality*, *vibrancy*, *resilience* and *socioeconomic sustainability*. Since this study is concentrating on the indicator-based approach for evaluation, additional key words such as *indicator*, *evaluation*, *index*, *indices* and *assessment*, were added to each research query. For limiting the results to papers concentrated on studying the rural or territorial vulnerability-vibrancy, key words identifying the type of populated area, such as *rural area*, *inner area*, *fragile area*, *rural territory*, *mountain*, and *villages*, were added to the queries. Additionally, for limiting furthermore the geographical coverage, papers containing the keywords *urban* or *city* in the title field were excluded. Some query-specific additional keywords were used in order to filter more effectively the results and refine the queries. On the basis of the considerations made, as a result 14 queries were constructed – 5 representing the negative aspect and 9 representing the positive one.

After the refinement of the results through the engine criteria of limitation and exclusion, the bibliographic data of the final research results was extracted.

Data Preparation. All the datasets downloaded from Scopus were used to create two databases – the first one reflecting the negative perspective of the research topic and the second reflecting the positive one. For the creation of Database 1, the datasets obtained from search queries 1–5 were merged together, resulting in 731 records in total. Instead, for the creation of Database 2, datasets 6–14 were used, resulting in 441 records in total. It is important to mention that these results are referred to the date 02/02/2023.

Afterward, it was proceeded with the elimination of the duplicates of the records in each of the two databases. In Database 1 56 duplicates were encountered, resulting in 675 final number of records (Fig. 2). Instead, in Database 2 57 duplicates were present, resulting in 384 final number of records (Fig. 2).

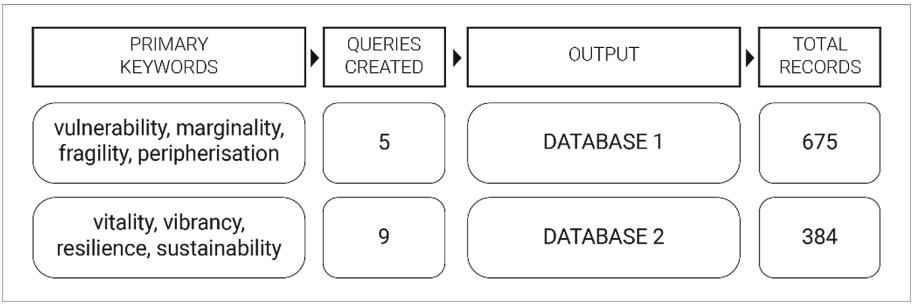

Fig. 2. Scheme representing the two created Databases and their total number of records, update date 02/02/2023 (Source: Authors' elaboration).

Data Analysis. For the construction of the visual maps the following analysis settings were chosen: analysis of the co-occurrence of the authors' keywords, using the full counting, setting the minimum number of occurrences of the keyword as 2, selecting all the keywords and visualising the largest set of connected items. This operation was performed for each of the two Databases. As a result, two visual maps were extracted: a first one constructed on Database 1, containing 215 final items/keywords, and a second one constructed on Database 2, containing 144 items/keywords.

Instead, for obtaining the quantitative information about all existing author keywords in the databases another settings combination was followed: analysis of the co-occurrences of the author keywords, using the full counting, setting the minimum number of occurrences of the keywords as 1, selecting all the keywords and visualising all of them. This operation was also performed for each of the two Databases. From Database 1 2341 keywords in total were extracted, instead from Database 2, 1489 in total. As a result, after running the analysis with the second combination of settings, for each Database were extracted the VOSviewer Map file and the VOSviewer Network file.

Database 1 - Authors' Keywords Analysis

From the map, visualising the keywords' occurrences and link strength, constructed on the basis of Database 1 (Fig. 2), can clearly be seen that a central position takes the keyword vulnerability. It is interesting to notice that 5 stronger clusters were formed on the map. The first in yellow, which is composed by the key words like *vulnerability*, *development, environment, rural, sustainable development, sustainable livelihoods*, etc., is showing the opposition of the sustainable development to the vulnerability. The second interesting cluster is the red one, containing keywords like *inner areas, land use, local development, marginalisation, territorial capital, territorial vulnerability*, showing the topic of the territorial development of marginalised areas. The third strong cluster is the orange one, containing terms like *accessibility, depopulation, inner peripheries, peripherisation, polarisation*, etc., showing the connection between the accessibility and the abandonment of the territory. The fourth one is the grey one, composed by terms like *GIS*, *ICT*, *multicriteria*, *fuzzy logic*, *urban planning*, *fragile area*, etc., showing some of the tools and techniques used in the urban planning discipline. The fifth cluster is the green one, containing keywords like *rural areas, rural community, renewable energies, quality of life*, a cluster showing the attention given to the study of aspects of the rural

life that has the potentiality to foster the development and to improve rural areas' living conditions (Fig. 3).

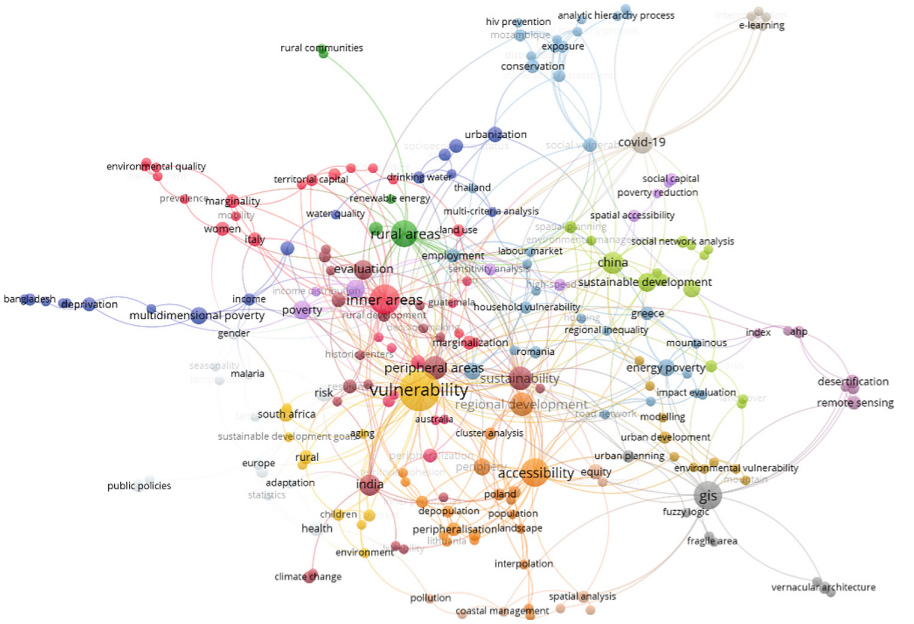

Fig. 3. Co-occurrence network visualisation of authors' keywords of Database 1, based on number of occurrences (Source: Authors' elaboration by using VOSviewer).

It is interesting also to observe the proximity of the terms on the map, showing the strength of the relation between them [23]. It is noticeable the vicinity and the connection between the terms *vulnerability* and *inner areas*, *vulnerability* and *sustainability*, *rural areas* and *inner areas*, *regional development* and *sustainability*, *regional development* and *accessibility*.

From the extracted Map file, it can be observed that the term *vulnerability* is the one with most occurrences (33 in total), the one with highest number of links (140 in total) and with the strongest total link strength (151 in total) (Table 1). The following most recurrent keywords are *inner areas*, with 18 occurrences, and *accessibility* and *GIS*, with 16 occurrences (Table 1). It is also interesting that the terms *vulnerability* and *inner areas* are appearing with higher difference between the Total link strength (indicating the number of publications in which two keywords occur together [22]) and the number of the links, showing that these terms have appeared in more than one publication in certain combination with some other keyword. From the extracted Network file, it can be seen that some of the term combinations (relevant for our research field) in which the keyword *vulnerability* appears in more than one publication are with the keywords *development*, *resilience*, *rural households*, *sustainability*. The same observations can be made for the keyword inner areas, which appears in more than one publication in combination with keywords such as *rural areas*, *territorial capital*, *territorial cohesion*,

territorial vulnerability. Another important observation is that from the most recurrent keywords there are some, in the field of interest of the studied topic, which are also quite recent. A term like this is *inner areas*, with average publication year 2020, and also *peripheral areas* and *accessibility*, with average publication year approximatively 2019. While the term *vulnerability*, even though with the highest number of occurrences, results as an older field of study with average publication year 2016 (Table 1).

Table 1. Extraction of the Map file showing the top 10 keywords of Database 1, ordered by the number of occurrences (Source: Authors' elaboration by using VOSviewer).

Keyword	Occurrences	Links	Total link strength	Avg. pub. year
Vulnerability	33	140	151	2016,03
Inner areas	18	67	75	2020,00
GIS	16	70	72	2017,44
Accessibility	16	69	72	2019,25
Rural areas	14	64	68	2016,57
Regional development	11	52	55	2017,36
Sustainability	11	48	50	2014,09
Peripheral areas	11	47	49	2019,55
China	10	46	46	2016,50
Covid-19	10	38	44	2021,40

From the Map file output, it is possible to observe that there is only one of the predefined keywords (*fragility*) that shows very low number of occurrences (only 2 occurrence). It is also interesting the position that the keywords originating from the term peripherisation take in the Map file, appearing in its pure form but in the same time also in a lot of different configurations, such as *inner peripheries*, *periphery*, *peripheral areas*, etc.

Database 2 - Authors' Keywords Analysis.
From the visual map constructed on the basis of Database 2 (Fig. 4), can clearly be seen that the term *resilience* takes a central position. It is interesting to see that there are 5 stronger clusters formed on the map. The first one is the purple one, containing terms such as *resilience*, *cluster analysis*, *UNESCO*, *village*, etc., which results as a quite heterogeneous cluster, showing that the concept of resilience can be associated to a lot of sub-fields of study. The second one is the red cluster, composed by keywords like *sustainability*, *urban development*, *poverty*, *food insecurity*, *food security*, *livestock*, *farming systems*, etc., giving attention to the importance of the food system for the sustainable development. The third cluster is the dark blue-grey in the bottom left, composed by keywords like *sustainable development*, *social sustainability*, *rural tourism*, *rural sustainable development*, *economic sustainability*, *environmental sustainability*, *community resilience*, etc., which is totally concentrated on the sustainable development in all its aspects. The fourth cluster if the dark blue one, composed by the keywords such as *rural*

areas, *rural development*, *sustainability assessment*, *decision making*, *boosted regression tree*, *interdisciplinarity*, *modelling*, *multifunctionality*, *participation*, etc., which is an interesting cluster showing some of the techniques used in the rural planning field. And the fifth cluster is the pink one, on the left part of the map, containing terms such as *rural*, *rural communities*, *aging*, *livelihoods*, *socioeconomic status*, etc., which is giving more attention to the study of the social structure of the rural areas.

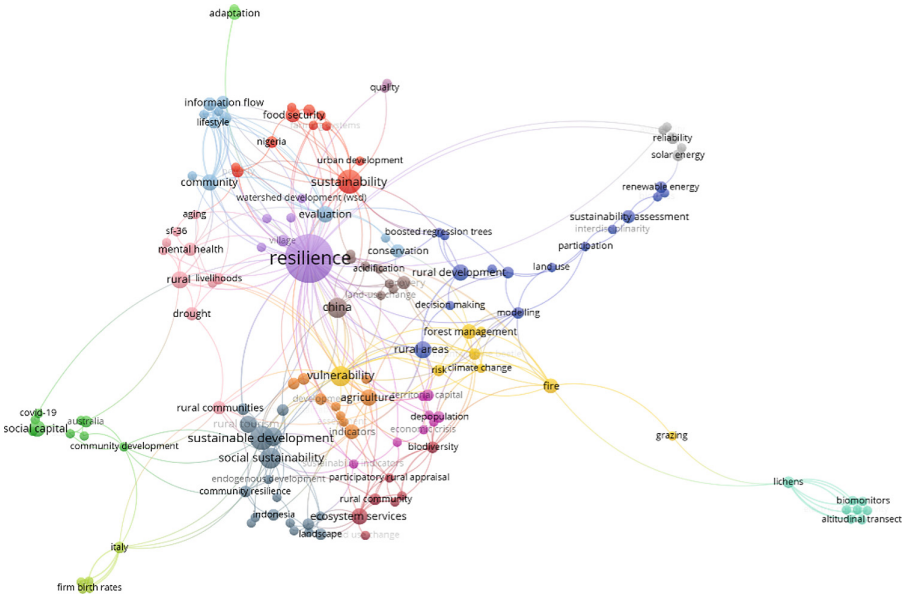

Fig. 4. Co-occurrence network visualisation of authors' keywords of Database 2, based on number of occurrences (Source: Authors' elaboration by using Vosviewer).

As mentioned before, it is also important to analyse the vicinity and the relations existing in between the different terms. It should be noticed the close connection between the terms *resilience* and *evaluation*, *resilience* and *sustainability*, *resilience* and *village*, between the terms *rural areas* and *rural development* but also *rural areas* and *vulnerability* and between *indicators* and *social sustainability* and *indicators* and *rural areas*.

From the Map file it also can be observed that the term *resilience* it is indeed the one with highest number of occurrences (53 in total), highest number of links (255 in total) and highest total link strength (271 in total) (Table 2). The other two most recurrent terms seem to be *sustainability* and *sustainable development*, with 13 occurrences for both of them (Table 2). It is interesting also the higher difference between the Total link strength and the number of links that the keywords *resilience* and *social sustainability* show, meaning that they appear in a certain combination with other keywords in more than one publication. From the Network file it can be observed that the keyword *resilience* appears in more than one paper in combination with the keywords *sustainability*, *vulnerability*, *rural*, *community*, *indicators*, *poverty*. The same analysis was performed for the keyword

social sustainability, which seems to appear in more than one study in combination with the keywords *sustainable development*, *economic sustainability*, *environmental sustainability*. Another interesting observation is that among the most recurrent keywords there are some that can be considered more recent, such as *sustainability*, *rural areas*, *rural tourism*, with average publication year 2019 (Table 2).

Table 2. Extraction of the Map file showing the top 10 keywords of Database 2, ordered by the number of occurrences (Source: Authors' elaboration by using VOSviewer).

Keyword	Occurrences	Links	Total link strength	Avg. pub. year
Resilience	53	255	271	2018,23
Sustainability	13	65	68	2019,31
Sustainable development	13	59	63	2018,77
Social sustainability	10	47	53	2017,70
Vulnerability	9	50	53	2016,22
China	9	39	39	2017,11
Economic sustainability	8	26	31	2013,38
Rural areas	7	36	38	2019,43
Rural	7	28	31	2016,57
Rural tourism	7	24	26	2019,14

Since it was noticed the absence of two of the main predefined keywords (*vitality* and *vibrancy*) in the map and in the list with the most recurrent keywords, it was made an extraction, by filtering the outputs contained in the Map file, relative only to these two keywords. It can be seen that these terms present low number of occurrences but very recent average publication years. Another interesting result is that they rarely appear in their pure form – only by themselves - but mostly in word combinations, which also tend to be quite heterogeneous. The one representing the term *vitality* are such as *space vitality*, *vitality assessment*, *rural vitality status assessment*, *community vitality*, *rural vitality* - giving attention to the field of the evaluation of the status of the rural space. Instead, the term *vibrancy* appears with only 1 occurrence, specifically in the form *territorial vibrancy*, showing a gap in this research field.

4 Discussion and Conclusions

The main research objective of the present paper is to examine the emerging research fields and gaps of the quantitative indicator-based approaches for the territorial and rural vulnerability-vibrancy evaluation in non-urban context.

The obtained results further prove the duality of the above-mentioned topic, confirming the existence of two perspectives from which the topic can be studied – originating from and gravitating between negative meaning phenomena and positive meaning ones.

In conclusion, firstly it can be said that generally the research of the given topic is more consolidated in its negative aspect, showing higher number of research results, earlier average publication years and higher heterogeneity in the research subtopics, which also tend to be quite strongly investigated. Furthermore, from the clusters analysis we can conclude that the topic, both when approached from its negative perspective and its positive one, is being studied in heterogeneous way, giving attention to different sub aspects – such as the tools and techniques that could be used, the importance of the sustainable development principles as opposition to the rural degradation, etc.

Considering the negative aspect of the research topic, it is possible to say that most consolidated subfields of study are the vulnerability and the peripherisation, followed by the marginality, which haven't achieved the same degree of investigation of the two mentioned before but still results more developed than the fragility, which results as rarely considered subfield. Even though the negative aspect has been widely studied, still there are some aspects of it that are more recent and can be seen as emerging ones, such as the question of the accessibility and the evaluation of the inner areas.

Instead, considering the positive aspect, it is possible to notice some consolidated areas of study, such as the resilience and the sustainability of the rural areas, but in the same time they appear some strong emerging subtopics, such as the ones originating from the term vitality. Instead, an interesting research gap shows to be the territorial vibrancy, that could become more investigated in the future years.

The further study of the phenomena of the vitality and the vibrancy and the establishment of a consolidated methodological approach for their monitoring could be of a great help to the decision-makers in the local territorial programming and funding for transformation and enhancement of a given territory.

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Sustainable Mobility Last Mile Logistic (ELLIOT 2023)

A Bi-objective Routing Problem with Trucks and Drones: Minimizing Mission Time and Energy Consumption

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Abstract. This paper addresses the *Vehicle Routing Problem with Drones* (VRPD), where the objective consists in creating shortest parcel delivery routes that are operated by a mixed fleet of trucks and drones. After formulating the VRPD as *Mixed Integer Linear Program* (MILP), we introduce a two-phase *Simulated Annealing* algorithm to solve the VRPD. Using benchmark instances, we conducted extensive computational experiments to prove the effectiveness of our algorithm. Additionally, we investigated the impact of using drones, not only on completion time but also on energy consumption of the truck-drone fleet under real-world resembling scenarios. Indeed, by optimizing for minimal makespan as well as minimal energy consumption, and by applying a bi-objective optimization model, the overall observation confirms substantial benefits of using drones on reduction of makespan and energy consumption. Thus, using a combined truck-drone fleet, last-mile logistics may become not only more cost-efficient but also more environmentally friendly and sustainable.

Keywords: Logistics · Vehicle Routing Problem with Drones · Mixed Integer Linear Program · Heuristic · Simulated Annealing

1 Introduction

With an increasing urban population and the rising popularity of e-commerce, the last-mile logistics faces many challenges. Local air and noise pollution, the emission of climate-damaging greenhouse gases, and exuberant traffic congestion are among the increasing external effects of last-mile logistics, which can make home deliveries environmentally damaging, economically inefficient, and opposing to the *Sustainable Development Goals* (SDGs), which are adopted by the United Nations, in particular Goal 11 that is directly linked to the sustainable development of cities[1]. However, thanks to recent innovations, including engine

[1] https://sdgs.un.org/goals.

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technologies and autonomous vehicles, these challenges might be resolved. In this context, the rapidly evolving drone technology has attracted attention of researchers and practitioners in the logistics sector. Indeed, since drones are not bound to the road network, they constitute an interesting new mode of transportation which makes it possible to escape road traffic, to reach certain destinations quickly, and to reduce environmental and social impacts [2,4]. The well-known technology companies, e.g., Alphabet, Amazon, and DHL, have shown interests in using drones for delivering parcels (see [15] and references therein).

In this context, ideas have emerged to use drones alongside trucks as assisting delivery vehicles. In fact, drones can be used to take parcels autonomously from a truck to a customer or the other way round. In this case, the truck is used as a mobile depot and carrier for drones, where the battery of drones can be replaced or recharged. Moreover, the truck can continue to serve other customers while the drone is airborne. Thus, the total mission time will decrease.

These concepts raise the question of how to plan last-mile logistics routes for such a combined trucks-drones delivery concept. On the one hand, the unique features of trucks and drones enable the possibility for efficiency gains, but on the other hand, they impose limits on the form of generated routes.

In order to obtain the best possible benefits in delivering parcels by a combined truck-drone fleet, several new optimization problems have been introduced, e.g., the *Traveling Salesman Problem with Drone* (TSP-D) [1,3,17,24,25] and the *Vehicle Routing Problem with Drones* (VRPD) [5,15,19–23,27,28], which are extensions to the classical *Traveling Salesman Problem* (TSP) and *Vehicle Routing Problem* (VRP), respectively.

In the context of the VRPD, the contributions of this paper are as follows:

- We introduce a bi-objective truck-drone routing model, and present a two-phase algorithm based on the *Simulated Annealing* (SA) metaheuristic to solve larger instances of the bi-objective VRPD.
- We present the numerical results of our extensive computational experiments on benchmark instances and realistic scenarios, i.e., on instances with parameters that approximate real-world scenarios, in order to investigate the impacts that drone-assisted delivery methods can have on makespan and in particular on energy consumption.

The remainder of this paper is organized as follows: After a brief literature review in Sect. 2, we present our notation and assumptions, a formal description of the VRPD, and its mathematical formulations in Sect. 3. To solve the VRPD, a two-phase Simulated Annealing algorithm is presented in Sect. 4. Section 5 is devoted to the numerical results of our computational experiments covering small and large benchmark instances with and without realistic-scenario assumptions. Section 6 contains our concluding remarks.

2 Literature Review

Detailed reviews on truck-drone delivery concepts can be found, e.g., in [15] and references therein. However, we present a short overview on a selection of papers that are closely related to the context of this paper.

In fact, we investigate a variant of the *Vehicle Routing Problem with Drone* (VRPD), which was introduced by Wang et al. [23,28]. In the VRPD, a set of trucks, where each truck is equipped with identical drones, is tasked to deliver parcels to a given set of customers in the shortest possible time. Compared to the classical vehicle routing problem (VRP), the VRPD has additional features, e.g., the delivery fleet is heterogeneous, one type of vehicles, i.e., the drone, has a limited carrying capacity and a restricted travel distance, and the VRPD requires synchronization constraints [21]. The VRPD was intensively investigated in, e.g., [13,15,19–23,27].

The VRPD can be formulated as a *mixed integer linear program* (MILP), which can then be solved by state-of-the-art MILP solvers, e.g., IBM CPLEX or Gurobi Optimizer [8]. As an extension to the classical VRP, the VRPD is known as an NP-hard problem for which it is impossible to find the global optima within reasonable time, if we use exact methods and the instance size is large [29].

In [22], the authors provide a hybrid approach based on tabu search and *variable neighborhood search* (VNS) [21] to solve the VRPD in presence of *en route operations*, i.e., the drones are able to start and end their mission at some discrete points on the road connecting two customers. In [23], the authors present a matheuristic, which decomposes the VRPD and solves *drone assignment and scheduling problems*. This approach is tested on instances with up to 100 customers. In addition, [23] introduces several classes of valid inequalities and investigates different variants of the VRPD.

In [27], the VRPD is formulated as a MILP, and a branch-and-cut algorithm for the VRPD is derived. The presented algorithm can optimally solve instances with up to 30 customers. The paper shows that using truck-drone tandems can not only improve makespan, but also reduce the fleet size without decreasing the efficiency of transportation systems.

In a recent paper, Masmoudi et al. studied a variant of the VRPD where drones are equipped with a multi-package payload compartment. To solve the problem, the authors use an adaptive multi-start simulated annealing. The algorithm is tested on some benchmark instances and the results are compared with a hybrid genetic algorithm [16].

Even though addressing large instances can currently be done only by heuristics and metaheuristics, these approaches cannot guarantee global optimality of the obtained solutions. However, a well-designed heuristic can provide high-quality solutions in reasonable computation time [16,29]. In this paper, we not only introduce an efficient simulated annealing algorithm to solve the VRPD, but also investigate two kinds of objective functions: *minimizing makespan* and *minimizing energy consumption*. To further bridge the research gap, in our numerical investigations, we use parameters that approximate real-world conditions.

3 The Vehicle Routing Problem with Drones

In this section, we present our assumptions, the notation that we are going to use throughout this paper, and the mathematical formulations of the VRPD.

3.1 Notation and Basic Assumptions

We assume that a depot, a set of customers, and a fleet of trucks are given such that each truck is equipped with a certain number of drones. Starting from the depot, the trucks and the drones have the mission of delivering parcels to the customers in the shortest possible time. Each customer is served exactly once, either by a truck or a drone. On a truck's tour, the assigned drones of the truck can launch from it, serve a customer, and return to the truck. This operation performed by a drone is called a *sortie*. Moreover, we accept the following assumptions on drone sorties and deliveries [3,21,22]:

- A drone can serve exactly one customer per sortie. However, a truck can serve several customers, even while its drones are performing a sortie. In addition, we assume that each truck has sufficient capacity for all deliveries.
- A drone can depart from and return to the same truck. Launching from or landing on a truck is only allowed when the truck is at a customer location or at the depot. The pickup of a drone cannot happen at the same customer location it was launched from, i.e., *cyclic sorties* are not permitted. For the return of a drone to a truck at a certain location, the drone may need to wait for the truck to arrive or the truck should wait for the drone.
- The flight endurance of a drone is limited to $\mathcal{E}$ distance units per sortie. Upon return to a truck, the endurance is restored immediately, which means a drone can be launched from the same node where it returned to the truck. We assume that the trucks have an unlimited endurance.
- Service times for delivering parcels by either drone or truck as well as the service and setup time for drone launching and retrieval are negligible.
- The drones' velocity is α times the trucks' speed. Since drones do not face traffic congestion or road priority rules, we can assume $\alpha \geq 1$.
- Risk-free: Drone deliveries always succeed once the drone has launched.

The objective of the VRPD is to minimize the mission time (*makespan*), which is the duration that it takes the vehicles to serve all customers and to return to the depot afterwards. To formulate the VRPD as a MILP, we need to present the required notation and decision variables [21–23].

Let $G = (V, E)$ be a symmetric complete graph, where V is the set of vertices (nodes) and E is the set of edges. The set $V = \{0, 1, \ldots, n+1\}$ contains n customer locations $V_N = \{1, \ldots, n\}$, and the depot nodes 0 and $n+1$. Both depot nodes, one at the beginning and one at the end of a tour, represent a single location ($0 \equiv n+1$). Moreover, we assume that the set $V_L = V \setminus \{n+1\}$ holds all nodes from which a drone can launch for a sortie, and $V_R = V \setminus \{0\}$ contains all nodes where a drone can be retrieved.

A *drone sortie* is defined by a tuple (i, w, j), where $i \in V_L$ denotes a *launch node*, w is a *customer node* that is served by the drone, and $j \in V_R$ is a *return node*, where the drone rejoins the truck.

We use d_{ij} and $\bar{d_{ij}}$ to denote the distance between nodes i and j for a truck and for a drone, respectively. The average velocity of the trucks and that of the drones is represented by v and $\bar{v}$, respectively, where $\bar{v} = \alpha \cdot v$. The travel time from vertex i to vertex j can therefore be stated as $t_{ij} = d_{ij}/v$ for trucks and $\bar{t_{ij}} = \bar{d_{ij}}/\bar{v}$ for drones. Furthermore, the set $K = \{1, \ldots, K_n\}$, $K_n \in \mathbb{Z}^+$ indicates that $|K| \geq 1$ trucks are available such that each of them is equipped with $D \in \mathbb{Z}^{\geq 0}$ drones.

As decision variables for the model, we use $x_{ij}^k \in \{0, 1\}$ to show whether the edge (i, j) is traversed by truck k. The variables $y_{iwj}^k \in \{0, 1\}$ state if the drone sortie (i, w, j) is part of the route of truck k, meaning that one of the truck's drones launches from node $i \in V_L$, serves customer $w \in V_N$ and returns to the same truck k at node $j \in V_R$ ($i \neq j$, $i \neq w$, $w \neq j$). With $p_{ij}^k \in \{0, 1\}$, we indicate whether node i is served at some point before node j (but not necessarily immediately before j) on the route of truck k. The integer variables u_i^k, having a lower bound of 0, show at which position the customer node i is possibly served through the truck k's route. To further specify the position of drone sorties, the variables $z_{aiwje}^k \in \{0, 1\}$ are used, where a value of 1 indicates that the launching node a of sortie (a, w, e) is placed on the route of truck k before node i, and the return node e comes after node j. This means that the drone is airborne while the truck makes deliveries at customers i and j. The continuous variables $a_i^k \geq 0$ specify the earliest arrival time of truck k at node i.

3.2 Mathematical Formulation of the VRPD

The MILP formulation of the VRPD is given in (1) – (19), where the objective function (1) minimizes the makespan under constraints (2) – (19).

$$\min \tau \tag{1}$$

$$\text{s.t.} \quad \tau \geq a_{n+1}^k \quad : \forall k \in K, \tag{2}$$

$$\sum_{j \in V_N} x_{0j}^k - \sum_{i \in V_N} x_{i,n+1}^k = 0 \quad : \forall k \in K, \tag{3}$$

$$\sum_{i \in V_L} x_{ih}^k - \sum_{j \in V_R} x_{hj}^k = 0 \quad : \forall k \in K, h \in V_N, \tag{4}$$

$$\sum_{j \in V_R} x_{0j}^k = 1 \quad : \forall k \in K, \tag{5}$$

$$\sum_{i \in V_L} \sum_{k \in K} x_{ij}^k + \sum_{l \in V_L} \sum_{m \in V_R} \sum_{k \in K} y_{ljm}^k = 1 \quad : \forall j \in V_N, \tag{6}$$

$$2y^k_{iwj} \leq \sum_{h \in V_L} x^k_{hi} + \sum_{l \in V_N} x^k_{lj} \quad : \forall k \in K, i \in V_N, w \in V_N, j \in V_R, \; i \neq j, i \neq w, w \neq j, \tag{7}$$

$$y^k_{0wj} \leq \sum_{h \in V_L} x^k_{hj} \quad : \forall k \in K, w \in V_N, j \in V_R, \tag{8}$$

$$u^k_i - u^k_j \leq (n+1)(1 - x^k_{ij}) \quad : \forall k \in K, i \in V_N, j \in V_R, i \neq j, \tag{9}$$

$$u^k_j - u^k_i \geq 1 - (n+1)(1 - y^k_{iwj}) \quad : \forall k \in K, i \in V_N, w \in V_N, j \in V_R, i \neq j, \tag{10}$$

$$u^k_i - u^k_j \geq 1 - (n+1)p^k_{ij} \quad : \forall k \in K, i \in V_N, j \in V_R, i \neq j, \tag{11}$$

$$u^k_i - u^k_j \leq -1 + (n+1)(1 - p^k_{ij}) \quad : \forall k \in K, i \in V_N, j \in V_R, i \neq j, \tag{12}$$

Constraints (2) are used to compute the arrival time of the last vehicle at the depot. Constraints (3) and (4) describe the flow conservations for the trucks and drones. The requirement that each truck has to start its route from the depot is stated in Constraints (5). Constraints (6) ensure that each customer is served exactly once by either a drone or a truck. Constraints (7) and (8) state the synchronization requirements on trucks and drones, and Constraints (9) – (12) deal with the order of the customer nodes within the routes. In particular, Constraints (11) and (12) connect the decision variables u^k_{ij} and p^k_{ij}.

$$3z^k_{aiwje} \leq y^k_{awe} + p^k_{ai} + p^k_{je} \quad : \forall k \in K, a \in V_L, i, w, j \in V_N, e \in V_R, \tag{13}$$

$$2 + z^k_{aiwje} \geq y^k_{awe} + p^k_{ai} + p^k_{je} \quad : \forall k \in K, a \in V_L, i, w, j \in V_N, e \in V_R, \tag{14}$$

$$M(x^k_{ij} - 1) + a^k_i + t_{ij} \leq a^k_j \quad : \forall k \in K, i \in V_L, j \in V_R, \tag{15}$$

$$M(y^k_{iwj} - 1) + a^k_i + \bar{t}_{iw} \leq a^k_w \quad : \forall k \in K, i \in V_L, w \in V_N, j \in V_R, \tag{16}$$

$$M(y^k_{iwj} - 1) + a^k_w + \bar{t}_{wj} \leq a^k_j \quad : \forall k \in K, i \in V_L, w \in V_N, j \in V_R, \tag{17}$$

Through Constraints (13)–(14), the decision variables p^k_{ij} and y^k_{awe} are used to determine the values of z^k_{aiwje}. In combination with the objective function, Constraints (15)–(17) compute the earliest arrival time at each node.

$$(\bar{d}_{iw} + \bar{d}_{wj}) y^k_{iwj} \leq \mathcal{E} \quad : \forall k \in K, i \in V_L, w \in V_N, j \in V_R, \tag{18}$$

$$\begin{aligned} M(x^k_{ij} - 1) + \sum_{v \in V_N} y^k_{ivj} + \sum_{l \in V_N} \sum_{\substack{m \in V_R, \\ m \neq j}} y^k_{ilm} + \sum_{\substack{p \in V_L, \\ p \neq i}} \sum_{q \in V_N} y^k_{pqj} \\ + \sum_{a \in V_L} \sum_{w \in V_N} \sum_{e \in V_R} z^k_{aiwje} \leq D \quad : \forall k \in K, i \in V_L, j \in V_R. \end{aligned} \tag{19}$$

Adherence to the drone endurance limit and to the maximum number of drones per truck are ensured by Constraints (18) and (19), respectively.

3.3 Valid Inequalities

Due to the NP-hardness of the VRPD, solving the model (1) – (19) with a standard MILP solver can be quite time consuming, except for small-sized instances

[5,15,19–23,27]. In order to enhance the performance of the MILP solvers, we can restrict the solution space by introducing valid inequalities. The following valid inequalities proposed by [21] have shown to be rather efficient, which is why we use them in our computational experiments too.

$$\sum_{i \in V_L} \sum_{j \in V_R} x_{ij}^k t_{ij} \leq a_{n+1}^k \quad : \forall k \in K, \tag{20}$$

$$\frac{1}{D} \sum_{i \in V_L} \sum_{w \in V_N} \sum_{j \in V_R} y_{iwj}^k (\bar{t}_{iw} + \bar{t}_{wj}) \leq a_{n+1}^k \quad : \forall k \in K. \tag{21}$$

In fact, the inequalities (20) - (21) place lower bounds on the arrival times a_{n+1}^k at the depot at the end of each route. Additionally, we use valid inequality (22), which sets an upper bound on the earliest arrival time a_{n+1}^k of the route for each truck k [21]:

$$\sum_{i \in V_L} \sum_{j \in V_R} x_{ij}^k t_{ij} + \sum_{i \in V_L} \sum_{w \in V_N} \sum_{j \in V_R} y_{iwj}^k (\bar{t}_{iw} + \bar{t}_{wj}) \geq a_{n+1}^k \quad : \forall k \in K. \tag{22}$$

3.4 Alternative Objective Functions

The objective function that is typically used in the VRPD models consists in minimizing the makespan [15,22,23]. However, it is plausible to consider costs minimization as alternative objective function (see [4,15,19], and references therein). Indeed, the usage of drones may be beneficial in terms of energy consumption for the following reasons. First, since aerial drones must be relatively lightweight, they cannot carry heavy batteries, which requires them to be as energy efficient as possible. Second, drones are not affected by road congestion and the related inefficiencies that make drones less pollutant. Hence, in this paper, we are interested in investigating the energy consumption of a VRPD solution too.

Energy Consumption Minimization. Let parameters c and $\bar{c}$ denote the energy consumption per distance unit for a truck and a drone, respectively. Then, by (23) we define an objective function for the VRPD to minimize the totally consumed energy. We denote this alternative VRPD by *VRPD-EC*, where *ec* stands for *energy consumption*.

$$min \quad c \sum_{k \in K} \sum_{i \in V_L} \sum_{j \in V_R} x_{ij}^k d_{ij} + \bar{c} \sum_{k \in K} \sum_{i \in V_L} \sum_{w \in V_N} \sum_{j \in V_R} y_{iwj}^k (\bar{d}_{iw} + \bar{d}_{wj}), \tag{23}$$

$$s.t. \ (3) - (19).$$

In terms of constraints for the VRPD-EC, the arrival times are still required for the synchronization of trucks and drones, but the earliest arrival time at the end depot has no effect on the objective value. Instead, the objective function minimizes the sum of the energy consumed on the individual edges by both trucks and drones.

Bi-Objective Optimization. While minimizing makespan or energy consumption as a single objective function, a generated route is not necessarily optimal in both dimensions simultaneously. Consequently, it might be favorable to generate delivery tours that constitute a meaningful trade-off between routes that are completed quickly but consume more energy versus routes that are the most energy efficient but take a significantly longer time to finish. This goal can be achieved in different ways, e.g., with a *bi-objective* optimization model. In the bi-objective VRPD, denoted by *VRPD-BI*, both objectives of minimizing the energy consumption and minimizing the makespan are included in a single model. To present the mathematical model of the VRPD-BI, let S denote the set of all feasible solutions of the VRPD-BI. Then, we define

$$g(s) = \tau \quad \& \quad h(s) = c \sum_{k \in K} \sum_{i \in V_L} \sum_{j \in V_R} x_{ij} d_{ij} + \overline{c} \sum_{k \in K} \sum_{i \in V_L} \sum_{w \in V_N} \sum_{j \in V_R} y^k_{iwj} (\overline{d}_{iw} + \overline{d}_{wj}),$$

where $s \in S$, $g(s)$ defines the latest arrival time of vehicles at the depot (makespan), and $h(s)$ computes the energy consumption of all vehicles for the VRPD-BI. Using this notation, the bi-objective VRPD is formulated as follows:

$$min \ \{(g(s), h(s)) : \quad s.t. \ (2) - (19)\}. \tag{24}$$

For any $s \in S$, the resulting tuples ($g(s)$, $h(s)$) can be assessed and compared with other results in terms of *Pareto* optimality [26].

4 A Simulated Annealing Approach for the Bi-objective VRPD

Due to the NP-hardness of the VRPD, using exact algorithms for solving the VRPD is limited to small-sized instances. To address large VRPD instances, we need to use heuristics and metaheuristics. In this paper, we develop a two-phase *Simulated Annealing* (SA) algorithm for solving the VRPD. Choosing SA is based on its ability in addressing complex combinatorial optimization problems such as the VRPD. Indeed, SA features a mechanism to escape local optima while at the same time it ensures, theoretically, convergence to a global optimum.

We design a two-phase heuristic, where each phase consists of a separate SA algorithm. The first phase creates a set of truck routes, i.e., VRP solutions, through a conventional SA and by solving the classical VRP without considering any drones [18]. In the second phase, the two-phase heuristic inserts drone sorties into the VRP routes to generate VRPD tours. The VRPD solution with the best objective value is returned as the final result of the algorithm. In the following parts of this section, we present each component of our SA algorithm.

4.1 The Metropolis Criterion

A basic SA starts from an initial solution, uses a temperature parameter to control the moves inside the search space, decreases the temperature, and generates

a solution within a neighborhood of the current solution. If the new solution has a better quality, then it is accepted and, if necessary, the incumbent solution is updated. If the new solution is worse than the current solution, then the SA permits to accept it under some conditions. This is an important feature of the SA, known as the *Metropolis* criterion, which is used to determine whether a solution with inferior quality should be accepted. Even though we solve single-objective as well as bi-objective VRPD models, for the sake of completeness, we formally define only the Metropolis criterion that we use in solving the bi-objective VRPD. The case of single-objective VRPD is defined similarly.

Let Ω denote the solutions set of the bi-objective VRPD, and the tuples $(g(\omega), h(\omega))$ consist of the makespan $g(\omega)$ and the energy consumption $h(\omega)$ at $\omega \in \Omega$. Generally, acceptance rules for multi-objective models can be described in terms of *Pareto* efficiency. More precisely, accepting a solution $\omega^{'}$ over ω with a probability of 1 if $\omega^{'} \succ \omega$ is called *strong criterion*, while the *weak criterion* ensures an acceptance if $\omega^{'} \not\prec \omega$, where the sign $\succ$ stands for dominance of a vector versus another one [26].

In this study, to have a better exploration of the search space, we use the weak criterion as the acceptance rule, i.e., all non-dominated solutions are always accepted. Moreover, we use an extended Metropolis criterion to decide if a new solution that is inefficient with respect to the current solution is accepted, i.e.,

$$P(\text{accept } \omega' \text{ as next solution}) = \begin{cases} \exp(\frac{-\Delta_{\omega,\omega'}}{t}), & \text{if } \omega' \prec \omega \ , \\ 1, & \text{if } \omega' \not\prec \omega \ , \end{cases} \tag{25}$$

where *exp* stands for the exponential function, $\omega \in \Omega$ is the current solution vector, and $\omega' \in \mathcal{N}(\omega)$, i.e., a solution in the neighborhood of ω. Moreover, $\Delta_{\omega,\omega'} = \sqrt{(g(\omega') - g(\omega))^2 + (h(\omega') - h(\omega))^2}$, and t is the temperature parameter at the current iteration (for more details, refer to [18] and references therein).

4.2 Simulated Annealing for Generating VRP Routes

The rational of the first phase of the algorithm is to generate a set of VRP tours, which supposedly constitute a good basis for drone insertions in the second phase. For this purpose, a commonly accepted approach consists in using a pool of different initial solutions, which can increase the chance of finding an optimal or a near-optimal VRPD solution. For this purpose, we start with an initial VRP tour x that is generated through a simple *route-first cluster-second* (RFCS) approach, which consists of applying a *Nearest-Neighbor-Heuristic* (NNH) in the route-generation phase, and an equal splitting by number of trucks in the clustering stage [11,20,21]. Afterwards, we continue by generating a random solution x' in the neighborhood $\mathcal{N}(x)$ for which we use a sequence of *2-opt*, *string cross*, *string relocation*, *string exchange*, and *string mix* operators [11,21]. Then, we check the quality of the new route and decide to accept or discard it by using the Metropolis criterion. We iterate the process until the stopping conditions, e.g., time limit or maximum number of iterations, are met. The set of best solutions found by this approach constitute the pool of initial VRP tours.

4.3 Simulated Annealing for the VRPD

In the second phase of the algorithm, summarized in Algorithm 1, drone sorties are integrated into the truck tours, which are generated in the first phase.

Algorithm 1. SA algorithm of the drone inclusion phase.

for each $x \in X$ **do**
  Set $y \leftarrow x$ and $t \leftarrow t_0$
  while $t \geq t_{min}$ or *iteration limit or time limit is not reached* **do**
    Generate a neighbor valid solution $y' \in \mathcal{N}(y)$
    Calculate objective value of the new route y'
    If required, use the Metropolis criterion to check acceptance of the new route
    if y' is accepted **then** $y \leftarrow y'$
    end if
    if $f(y') < f(y^*)$ **then** $y^* \leftarrow y'$
    end if
    Update the temperature and iteration parameters
  end while
end for
return y^*

The algorithm's input is a VRP solution pool X, and the output is y^*, which is the best of the resulting VRPD solutions. The outer loop iterates over the initial VRP solutions in X to generate VRPD routes and to optimize them through an SA. Furthermore, whenever a neighbor solution with a better objective value is found, y^* is updated to save the overall best VRPD solution.

Compared to the VRP, the solution space of the VRPD is highly constrained. Hence, the selection of a valid $y' \in \mathcal{N}(y)$ can be time-consuming. To avoid excessive search for valid neighbor solutions, we impose a limit on the number of attempts such that in case of failure in finding a valid solution, the algorithm continues with the next VRP tour from the set X.

In producing VRPD routes out of VRP truck tours, generating valid neighbor solutions and updating the temperature parameter t are essential parts of Algorithm 1. In the following, we describe these components.

4.4 Drone Sortie Operators

Assume that a set of VRP truck tours is given. Then, we generate valid VRPD routes by integrating drone sorties into the truck routes through applying two sets of operations: *basic drone operations* and *high-level operations*.

Any basic drone operation consists in performing either a *basic sortie insertion*, or a *basic sortie removal* operation. The *basic sortie insertion* operation is applied on a truck tour for a set of launch, customer, and return nodes to launch a drone from the launch node, serve the customer node, and land on the truck at the return node. An insertion operation is accepted only if the generated

route satisfies all constraints of the corresponding VRPD model. The *basic sortie removal* operation works in a similar but in reverse way, i.e., a drone sortie is removed from a given VRPD route. However, in this case, a validation check is not necessary as a drone sortie can always be successfully removed from a route.

Compared to the basic drone operations, the high-level operations define the neighborhoods of a given VRPD solution. In the following, we explain briefly the different high-level operators that we use in the algorithm.

For a given VRP or VRPD route, the *Insert Random* and *Remove Random* operators select one customer node randomly and insert or remove a drone sortie, respectively. The *Delivery Exchange* operator attempts to switch the delivery mode of a drone customer by turning it into a truck customer and vice versa [20]. The *Sortie Modify* operator attempts to modify a randomly selected existing sortie of a random route. The *Insert Best* is a more elaborated operator, which searches for a drone insertion that would result in the highest *savings* in terms of makespan and/or energy consumption through considering all vertices that could be turned into a drone node by adding a sortie without violating the VRPD constraints. To avoid computational operations, the range of the potential launch and return nodes is limited by a *maximum sortie range* parameter [21].

4.5 Cooling Schedule Determination

Since the cooling schedule has considerable impact on the performance of an SA algorithm, we propose a mechanism to find a suitable cooling schedule based on probabilities and instance characteristics.

A cooling schedule consists of an initial or start temperature t_0, a minimum temperature threshold t_{min} for the end of the cooling process, and a cooling factor $\delta(t)$, which sets the speed of transition from t_0 to t_{min}. Moreover, we denote the probability for hill-climbing moves at t_0 as P_0 and at t_{min} as P_{min}. Due to the Metropolis acceptance criterion, these values affect the probability for an inferior-quality solution to be accepted by the algorithm. Thereby, they influence the way in which the solution space is explored in the course of the algorithm. Indeed, due to the Metropolis criterion (25), we know that:

$$t = \frac{-\Delta_{\omega,\omega'}}{ln(P)}. \tag{26}$$

Hence, given $\Delta_{\omega,\omega'}$ at two neighbor solutions ω and ω', we can set desired acceptance probability values to the parameter P to find the temperature values t_0 and t_{min}. But, since we do not know the $\Delta_{\omega,\omega'}$ values at t_0 and t_{min} beforehand, we adopt a proxy value Δ_{Avg}, which is supposed to represent the average distance between neighboring solutions in the solution space. Therefore, before setting values to t_0 and t_{min}, the value of Δ_{Avg} is computed through preprocessing the solution space of each problem instance [12]. More precisely, the mechanism consists of estimating Δ_{Avg} by executing 100 sequential random moves from an initial solution and aggregating the resulting distances. Although the computed value is just an estimation of the true value, the resulting value supposedly

reflects some characteristics of the considered problem instance. To describe the procedure, we define $\delta(t) = \theta \cdot t$, where $\theta < 1$ is the cooling parameter and t is the current temperature level at a given iteration of the SA. Algorithm 2 provides the pseudocode of the cooling schedule mechanism, where the calculation of Δ_{Avg} in lines $1-6$ is followed by assigning values to t_0, t_{min}, and θ. Moreover, I_{total} and i_{max} are user-specified values indicating the total number of iterations of the heuristic and the number of iterations per temperature step, respectively.

Algorithm 2. Determination of the cooling schedule parameters.

1: Set $\Delta_{Avg} \leftarrow 0$
2: **for** q = 1 to 100 **do**
3: $\omega' \leftarrow$ *neighbor solution* $\in \mathcal{N}(\omega)$
4: $\Delta_{\omega,\omega'} \leftarrow f(\omega') - f(\omega)$ and $\Delta_{Avg} = \Delta_{Avg} + (\Delta_{\omega,\omega'} - \Delta_{Avg})/q$
5: Set $\omega \leftarrow \omega'$
6: **end for**
7: $t_0 \leftarrow -\Delta_{Avg}/ln(P_0)$ and $t_{min} \leftarrow -\Delta_{Avg}/ln(P_{min})$
8: $\theta \leftarrow exp\left(ln(\frac{t_{min}}{t_0})/\frac{I_{total}}{i_{max}}\right)$
9: **return** t_0, t_{min}, and θ

5 Computational Experiments and Numerical Results

We have conducted extensive computational experiments in two main parts: benchmark investigations and realistic scenarios. In this section, we present the numerical results and our observations.

5.1 Settings of Experiments

We selected instances from Agatz et al. [1], which are well-known in the literature, and are in two types: the *uniform* and the *single-center* (for details, refer to [1]). For the sake of an effective presentation of the results, we partition the selected instances into two classes of *small instances*, with between 5 and 9 nodes, and *larger instances* ranging from 10 to 100 nodes. In addition to the number and distribution of customers, the instances are characterized by the following parameters: the number of trucks $|K|$, the number of drones per truck D, the truck speed v, the parameter α (where, drone speed $\bar{v}$ is related to v by $\bar{v} = \alpha \cdot v$), and the relative drone endurance $\mathcal{E}_r$, which is specified as follows:

$$\mathcal{E} = \mathcal{E}_r \cdot max(E) \ : \ \mathcal{E}_r \in [0, 2], \tag{27}$$

where $max(E)$ is the longest Euclidean distance between any two nodes [22]. A value of $\mathcal{E}_r$ close to zero signifies a very limited drone endurance, whereas no endurance limit is imposed with $\mathcal{E}_r = 2$.

Regarding the benchmark experiments, we use the instance parameters $|K| \in \{1, 2, 3\}$, $D \in \{1, 2, 3\}$, $\alpha \in \{1, 2, 3\}$, $\mathcal{E}_r \in \{0.4, 0.6, 1, 2\}$, and $v = 1$. For each

instance size and distribution type (either uniform or single-center), we selected 5 instances. Each of them is combined with the various instance parameters, resulting in $3 \cdot 3 \cdot 3 \cdot 4 = 108$ instance combinations. In total, this results in 5400 VRPD instances for the small benchmark experiments and the same amount of instances for the larger benchmark experiments.

The realistic scenarios, tested on single- as well as bi-objective VRPD, are composed of instances containing 50, 75, and 100 nodes, and we used the parameters $|K| \in \{1, 2, 3\}$, $D \in \{1, 2, 3\}$, and different set of values for α, $\mathcal{E}_r$, and v (for details, refer to Sect. 5.4).

The Simulated Annealing parameters, which affect the efficiency of the algorithm, were determined by preliminary experiments using various problem instances from [1] and the TSPLIB[2]. These parameters are used by the cooling schedule mechanism explained in Sect. 4.5. For the truck route generation SA (respectively, drone inclusion SA), the value of P_0, P_{min}, I_{total} are set to 0.0464, 0.0, and $1000 \cdot n^{1.4}$ (respectively, 0.5, 0.0, and 20000).

We conducted all computational experiments on the *High Performance Computing* (HPC) cluster of the *RPTU Kaiserslautern-Landau* (Germany). The runs were executed on Intel XEON CPUs with a base frequency of 2.60 GHz. On the software side, we used the Java SE 11 JDK on Linux, having access to 32 GB of RAM per process. Since the second phase of our algorithm is the most time-consuming part, we set a time limit of 10 minutes per run. Each instance is ran 5 times, adding up to in total 62100 runs of the algorithm.

To benchmark the obtained values for the small instances, we compare the results of the SA with optimal values of the MILP (1) – (22) formulation of the VRPD. For this purpose, the model is implemented in Java and solved by the commercial solver Gurobi Optimizer in version 8.1.1 [8].

5.2 Small Instances

We used small benchmark instances, with $5 \leq n \leq 9$, to assess the performance of our algorithm in solving the VRPD, for which the solutions obtained by the SA are compared to those provided by the MILP solver Gurobi Optimizer [8].

Table 1 shows the comparative results for the small benchmark instances, broken down by the number of nodes $|V|$. As indicated in the second and third columns of Table 1, the SA algorithm solves a majority of the instances to optimality. These columns present the percentage of instances for which the SA has reached the optimal objective value in at least one and in all of the five runs.

According to the numerical results, even in cases where the algorithm does not reach the optima, the obtained solutions approximate closely the optimal objective values, i.e., with a small optimality gap up to 2.09% on average.

5.3 Larger Instances

Due to the complexity of the VRPD, the MILP solvers cannot find the optima of the larger VRPD instances within a reasonable computation time. Hence, this

[2] Available at http://elib.zib.de/pub/mp-testdata/tsp/tsplib/tsp/.

Table 1. Percentage of small benchmark instances optimally solved by the heuristic, average objective value gap, and runtime comparison with the solver.

$\|V\|$	Opt. found	Opt. in all runs	Gap	Avg. runtime [s]	
				solver	heuristic
5	93.70%	93.70%	0.50%	0.41	0.88
6	96.20%	95.93%	0.35%	1.67	1.64
7	90.19%	89.63%	0.83%	19.85	2.32
8	84.72%	83.06%	1.59%	157.88	2.88
9	71.94%	68.89%	2.09%	998.98	3.36
Total	87.35%	86.24%	1.07%	235.76	2.22

Table 2. Average computation time for each instance size and type as well as percentage of the instances for which the runtime limit (600 s) is reached.

	Instance type	Instance size $\|V\|$				
		10	20	50	75	100
Runtime [s]	single-center	4.41	17.51	170.30	363.94	545.10
	uniform	4.12	16.44	134.52	359.84	476.09
Limit reached	single-center	0.00%	0.00%	1.41%	15.19%	59.81%
	uniform	0.00%	0.00%	1.22%	19.48%	43.41%

section is devoted to presenting our results and observations from solving larger VRPD instances with our SA algorithm. To this aim, for each instance size, Table 2 presents the average runtime (in seconds) as well as ratio of runs for which the time limit of 600 seconds is reached. We observe that, by increasing the number of nodes, the average runtimes exhibit a polynomial growth. In addition, we see that, on average, the computation time for the uniform instances is consistently lower than the time required to solve single-center instances.

5.4 Realistic Scenarios

In our further experiments, we investigated using realistic scenarios in the VRPD. For this end, we used our SA algorithm to solve the MILP formulation of the VRPD as a single- as well as a bi-objective optimization problem.

Assumptions on the Realistic Scenarios. The realistic scenarios are based on both the uniform and single-center instances with 50, 75, and 100 customers, which are originally spread on a plane of 100×100 units in case of the uniform instances, and within or nearby around a circle with a radius of 50 units in case of the single-center instances [1]. With the objective of creating realistic conditions, we converted the customer location data to meaningful values in a physical distance unit. For this purpose, we scaled the instance planes to $\frac{1}{3}$ of

their original values, and treated them to be in kilometers, which makes the instances mimic large urban areas where the customers are situated within an area of about 1100 km^2. This constitutes an approximation of metropolitan areas of large cities, e.g., a bit larger than Berlin.

We used average truck speed values that are based on two empirical surveys, which determine average speed in urban areas worldwide. According to the surveys, the average speed of cars in city centers and urban areas are approximately 20.7 km/h and 31.2 km/h, respectively [7,10]. There is less empirical data available for drone speed levels; however, values between 64 to 80 km/h seem to be realistic for state-of-the-art commercial drones [6]. The flight endurance of these kinds of drones typically ranges between 10 and 50 minutes [9].

Along with these values, we define the *high-traffic* and *low-traffic* road congestion scenarios that correspond to the truck speed v of 20 km/h and 30 km/h, respectively. The velocity of the drones in both scenarios is assumed to be 60 km/h, constituting the low end of the maximum speeds of real drones. The endurance of the drones is assumed to be 20 minutes of flight time, which corresponds to a maximum distance of 20 km at the drone speed of 60 km/h.

To compute the energy consumption of drones, we use a linear model, empirically validated with an ArduCopter Hexa-B hexacopter drone [5], where for a fixed average payload of 1.5 kg, the energy consumption is expressed as follows:

$$E_{drone}(t) = (0.217 \cdot 1.5 + 0.185) \cdot t = 0.5105 \cdot t \text{ [kWh]}. \tag{28}$$

Concerning trucks, we use the energy consumption specification of an electric truck, i.e., Volkswagen e-Crafter, which is available to the mass-market and the corresponding detailed information is publicly available. More precisely, in the *New European Driving Cycle* (NEDC) [14], considering an average speed of 33.4 km/h, Volkswagen e-Crafter's energy consumption with a payload of 975 kg is stated as 21.54 kWh/100 km. Our selected values for low- and high-traffic scenarios are good approximations of these empirical values. Taking into account the empirical data, for a given value of the speed parameter v, the deduced energy consumption of an electric delivery truck is computed as follows:

$$E_{truck}(t) = 21.54 \cdot \frac{v}{100} \cdot t \text{ [kWh]}. \tag{29}$$

Makespan and Energy Consumption Results. Fig. 1 visualizes the results of the experiments with the realistic instances, using the makespan minimization, the energy consumption minimization, and the bi-objective minimization as optimization objective functions. In this figure, the average results, both in terms of makespan and energy consumption, are displayed for the different numbers of trucks, numbers of drones, and (low- as well as high-) traffic scenarios. The VRP tours, i.e., $D = 0$, are used as baseline to measure improvements that we gain by the insertion of drones.

As expected, while minimizing the makespan, there is a significant reduction in total mission time. Moreover, the marginal improvement per vehicle is diminishing for an increasing number of drones per truck and for a growing number

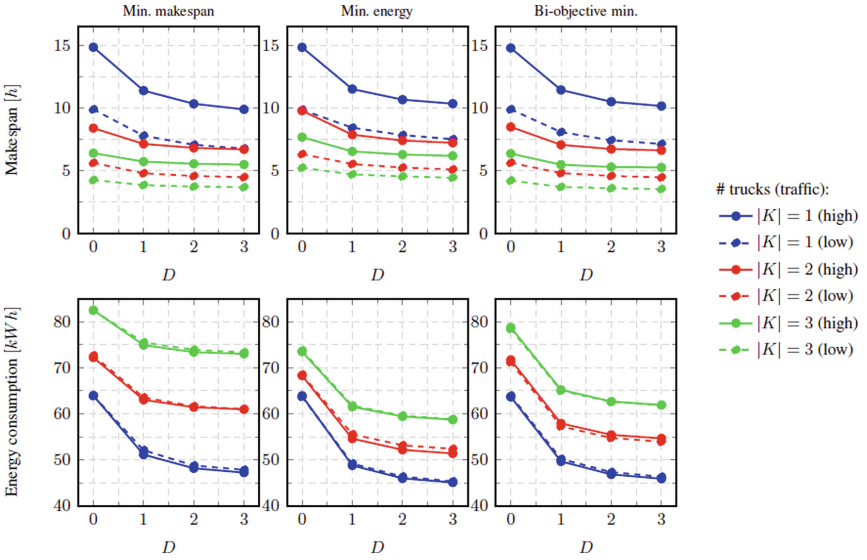

Fig. 1. Makespan and energy consumption results for the realistic scenarios.

of trucks. Indeed, the benefits of drone assistance are more pronounced in the high-traffic than in the low-traffic scenario because drones' trajectories are not affected by road congestion. Moreover, the minimal-makespan routes exhibit a drastic reduction in energy consumption when featuring drone operations.

While minimizing the energy consumption, we observe that the makespan values are slightly higher than what we obtain by using the minimal-makespan objective function (compare the left-side and middle parts of Fig. 1). Indeed, when $D \in \{2, 3\}$, the baseline optimal values (i.e., delivery routes in absence of drones) are significantly higher with the minimal energy consumption objective. This leads to higher overall makespan values; even though, the SA algorithm reduces them by a similar order of magnitude when drone sorties are integrated.

By solving the bi-objective VRPD, we expect to generate solutions that exhibit a compromise between a lower makespan and a reduced energy consumption. In fact, the resulting energy consumption values from the bi-objective optimization model, as visualized in Fig. 1, turn out smaller than the respective results from the makespan minimization model and larger than those obtained by solving the single-objective VRPD minimizing energy consumption. However, we observed that some makespan values of the bi-objective model not only drop below the respective results of the energy-consumption objective, but also smaller than outcomes of the makespan objective, even though the gap is quite small. This means that, with these instances, the makespan objective values are surprisingly dominated by the respective bi-objective results.

Finally, as we observe in Fig. 1, the energy consumed by the truck-drone fleet in high traffic is up to 1% lower than in low traffic, i.e., in terms of energy consumption, using drones may be equally beneficial in both scenarios.

6 Conclusion

This paper focuses on solving the *Vehicle Routing Problem with Drones* (VRPD) with a *Simulated Annealing* algorithm, where the VRPD is studied with different objective functions: minimization of makespan, minimization of energy consumption, and both of them simultaneously as a bi-objective optimization model.

Through extensive computational experiments on benchmark instances, we showed the efficiency of our SA algorithm that integrated an automated cooling schedule mechanism. Moreover, we investigated reductions in mission time and in total energy consumption under realistic scenarios, e.g., realistic vehicle speeds for two congestion levels, and inclusion of energy consumption models for both delivery vehicle types. Comparing the solutions, which are obtained by solving the single- and bi-objective VRPD models, we find a range of different outcomes confirming the benefits of drone-assisted deliveries also in realistic scenarios, not only in improving makespan, but also in reduction of energy consumption.

The presented algorithm solves the bi-objective optimization problem in reasonable computation time; however, developing an efficient exact algorithm is also a plausible future research direction to pursue. The research in this direction is in progress, and the results will be published in the future.

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Pick-Up Point Location Optimization Using a Two-Level Multi-objective Approach: The Enna Case Study

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Abstract. The E-commerce sector has experienced considerable growth and is connected to a growing demand for urban logistics services. It could have huge impacts on cities and the environment. The goal of the companies is to make the system more efficient, for example, by optimizing delivery tours. In general, sustainable logistics aims to reduce the carbon footprint, pollution and waste at all stages, including the distribution of goods to the end customer. Hence the need to balance the different social, economic and environmental objectives. The explosion of e-commerce has transformed consumer habits; new distribution standards, such as same-day deliveries, have multiplied the number of trips in city centers. Other problems emerge, particularly the fragmentation of deliveries and unattended deliveries. Companies must not neglect the environmental impact of their actions since reducing greenhouse gas emissions is one of the most significant challenges of our time.

Alternative shipping methods, such as pick-up points, allow deliveries to be concentrated in fewer points. In addition, this distribution mechanism benefits consumers by giving them maximum flexibility by letting them choose when and where to pick up their parcels. Although some European examples show that collection and delivery points offer a sustainable solution, this is not always true. This paper investigates the walking accessibility of collection and delivery points in a small urban centre in Sicily using spatial syntax methodology, calculating 5-min isochrones and evaluating walking infrastructures. The paper focuses on a particularly innovative topic, highlighting access to pick-up points from a user perspective and proposing a methodology that considers different aspects of the urban environment.The results show that good spatial accessibility of the pick-up points is not always linked to an equally good level of population coverage and the goodness of the associated pedestrian infrastructures.

Keywords: Pick-up points · Collection-and-delivery points · Urban logistics · Sustainability

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1 Introduction

The main challenges to be addressed in the coming decades have been signed and sub-signed by 193 UN member countries. These are summarised in the 17 goals of 'Transforming our world: the 2030 Agenda for Sustainable Development' [1]. These themes are closely connected to goals 13, 9 and 11 of Agenda 2030. Goal 13 stresses taking urgent action to combat climate change and its impacts for its general implications on the reduction of CO_2 emissions. Goal 9 emphasizes building resilient infrastructure, promoting inclusive and sustainable industrialization and fostering innovation, representing the focus from a business and, thus, a supply-side perspective. However, Goal 11 underlines to make cities and human settlements inclusive, safe, resilient and sustainable, representing the demand-side system regarding citizens and end-consumers. These three objectives are central to research in the area of urban transport [2]. Due to their characteristics, E-commerce and last-mile logistics represent sectors affected by the abovementioned objectives.

B2C (Business-To-Consumer) e-commerce is one of the most important research topics [3]. E-commerce, buying goods online with home delivery, and the impact on last-mile logistics that this practice has had, have evolved significantly over the last twenty years. The E-commerce growth trend has been considerable in the last few years. Statistics (as shown in Fig. 1) reveal that the total sales volume has tripled over the previous six years. At the same time, approximately one billion dollars more was increased in 2021 compared to the 2020 trend. This trend was largely influenced by the COVID-19 pandemic and the associated restrictions [4].

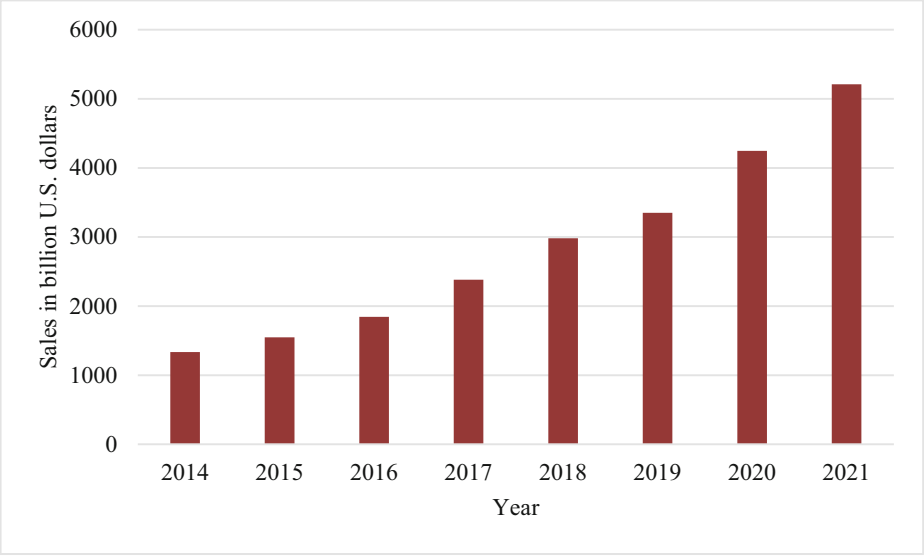

Fig. 1. E-commerce trend in the last decade. Source: Statista [5]

The growth of e-commerce has led to a restructuring in the habits of logistics companies [6]. The main feature has been to change the structure of the distribution supply chain [7]. Whereas the 'classic' supply chain sees the producer linked to the consumer via an intermediary, such as the retailer, now the producer/distributor comes into direct contact with the user. It has led to two significant consequences:

- the change in the habits of the user, who can choose direct-to-home delivery, influencing home-shopping mobility;
- the need for companies to equip themselves with efficient tools to optimize delivery tours.

Among the consequences of the rise of e-commerce at the urban level are:

- The fragmentation of deliveries. In 'classic' city logistics, the distributor has to deliver large quantities to a few points, located at retailers. In contrast, the current scheme involves deliveries of small quantities to many points;
- Consequently, the increase in vehicular touring has led to increases in negative externalities, pollution, CO2 emissions and accidents.

Among the emerging problems related to e-commerce is that of non-delivery. The customer's absence at home causes an empty trip and requires a re-trip. The benefit of tour optimization is thus lost, and instead, the negative externalities already highlighted increase [8].

The pick-up point is among the tools the distribution company and users have to deal with this problem [9]. Pick-up points are points, often located at public activities, representing a decoupling node in the supply chain at the last mile: the distributor deposits the parcels at the node, and customers can pick up the parcels by going to the node [10]. The scheme is substantially modified according to the image described in Fig. 2.

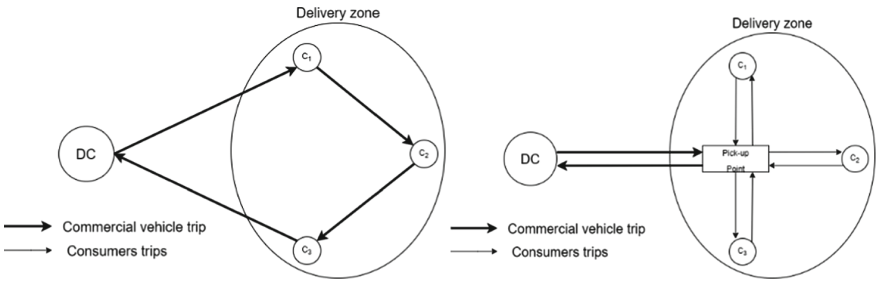

Fig. 2. Classic delivery scheme (left) and the implementation of a pick-up point (right)

Once a delivery zone is identified, the company reduces the number of pick-up points, resulting in fewer vehicle trips. The advantages of pick-up points are emphasized in the literature. In particular, some researchers have highlighted, starting from the study of different European countries, how pick-up points have decreased missed deliveries, optimized tours and reduced operating costs [11]. However, the decrease in vehicle trips has been matched by an increase in users' home-to-shopping trips. The user no longer has to travel to the retailer but to another point that performs the same function.

The user's home-shopping trip can take place in two ways:

- the displacement is generated solely by the need to go to the pick-up point;
- the movement occurs for other reasons (home-work, home-study, etc.) and thus only adds another element to the trip chain.

In the present work, the first motivation, trips generated by the need to travel to the pick-up point, is analyzed. In literature, it is shown how, in the case where the user uses a private vehicle such as a car to travel to the pick-up point, the benefits of the location of the pick-up point are cancelled out; this mainly occurs when the user is more than 5 min' walk from the point [12]. Therefore, the greatest possible demand coverage should also be considered when positioning pick-up points. This choice is made without considering a medium to long-term horizon; it is seen more as a new and different alternative offered to the user than as a tool to reduce negative externalities [13].

This article develops a methodology to evaluate the pick-up point network in an urban reality. Particular focus is given to small- to medium-sized realities, where a good optimization of traffic flows may be the source of a noticeable improvement in community life. To this end, the following elements are assessed in the proposed methodology.

- the pedestrian accessibility at 5 min from each pick-up point, with the instrument provided by the isochrones; this element allows for an assessment of the potential demand contained within the area relative to the point under consideration;
- the topological accessibility of each point, assessed using the instruments of the space syntax; the integration measure makes it possible to assess the position of a point in the network, and is an element characterizing the supply system. Reference is made to the discussion by Hillier et al. [14], also considering the high range of applications of space syntax present in the literature [15];
- the characteristics of the pedestrian infrastructure and the actual pedestrianization of the area surrounding the individual point considered.

The novelty of the research lies in the analysis of the positioning of pick-up points in an urban centre. The novel findings will help decongest the traffic flow by reducing tours and thus emissions and improving the pedestrianization of the area to allow for better user accessibility.

Section 2 presents the considered case study, the urban reality of Enna, a municipality in the South of Italy. Due to its characteristics describing the study area and underlining some particularities and issues. The methodology necessary to specify the objectives and identify a solution path is presented in Sect. 3. Section 4 presents the results of the study. Finally, Sect. 5 summarises some conclusions and proposes future developments.

The research is mainly addressed to different types of addressees: public administrators and technicians, to support planning strategies and implementations in urban realities, logistics companies for the implications contained within the overall objectives, and researchers who develop operational models that have social and environmental goals along with optimization of efficiency.

2 Study Area

The study area identified for the research is the area of Enna Alta, one of the two parts of the municipality of Enna. Enna is a municipality of approximately 25,000 inhabitants located in the central part of Sicily, in the extreme south of Italy, the provincial capital of the same name. Enna Alta constitutes the city's historical centre and is built on top of a hill. Therefore, it is naturally bounded by the steep walls of the hill. The total number of inhabitants of the area studied is 15,229 [16].

The geographical positioning of the area of Enna Alta, on top of a plateau, determines certain urban and geographical characteristics that make the study of this reality interesting:

- A highly interconnected road network internally, but with few points of contact with the external area, which naturally delimits the study area;
- Very high and variable average slope characteristics due to the orography of the area;
- High presence of steps within the urban area, as there are axes entirely composed of steps.

Twelve pick-up points were identified within this area, referencing those available from Amazon [17], and the analyses were conducted on QGis [18]. Figure 3 shows the distribution of pick-up points.



Fig. 3. Urban area studied and pick-up points

A first evaluation reveals an essential element: the pick-up points tend to be aggregated into two clusters on a territorial basis: a group in the East area (points 1-2-3-4-5) and a group in the West area (7-8-9-10-11), with only point 6 separated from the two groups.

The main characteristics of the urban network of Enna are then summarized. The average slope range on the acceptable arches is 0–0.5%, while pavement with good characteristics is greater than 1.50 m in width. Figure 4. And Fig. 5 show the slope and functional characteristics of the network arches.

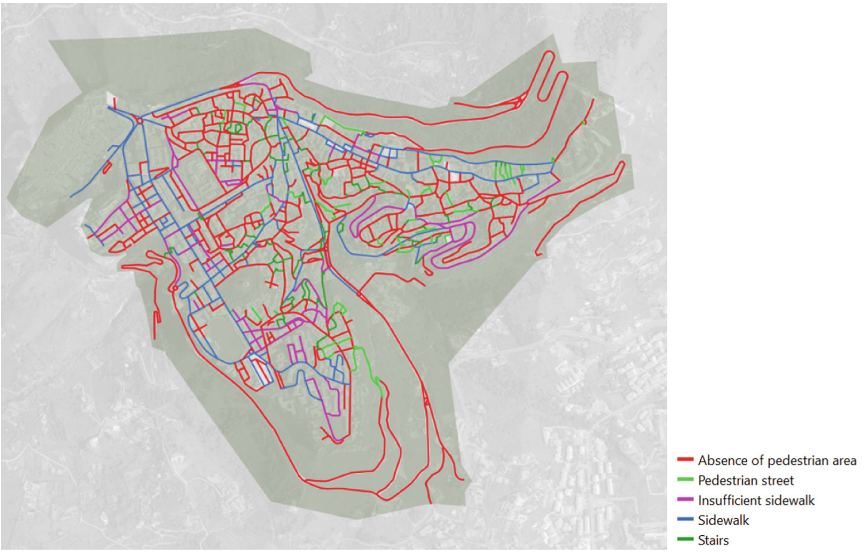

Fig. 4. Walking infrastructures classification

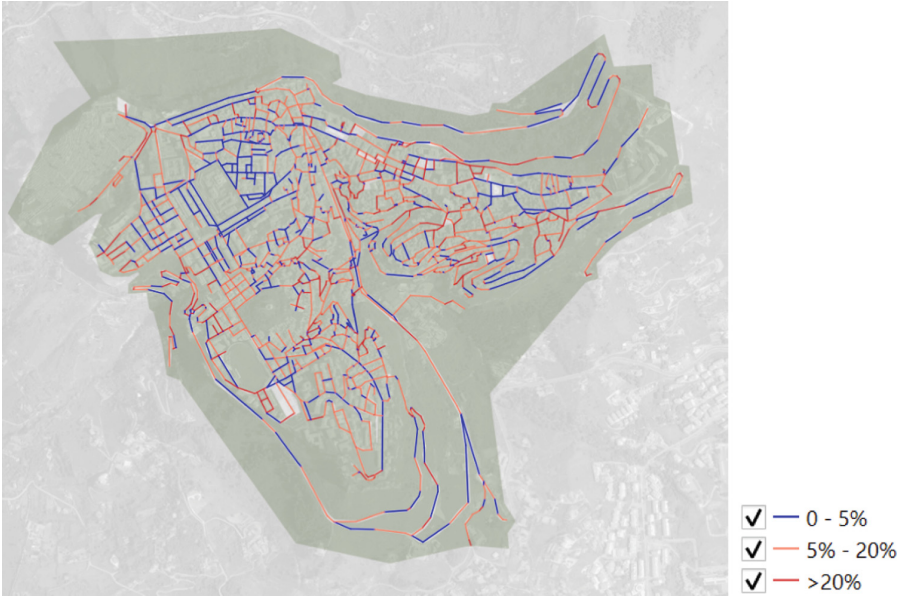

Fig. 5. Average road slopes

Table 1 shows the characteristics of the pedestrianization of the area.

Table 1. Pedestrianization of the area in percentages. Pedestrianization of the area in percentages.

Type of arc	% of the total network
Sidewalk	21%
Pedestrian street	5%
Stairs	6%
Insufficient sidewalk	13%
Absence of pedestrian area	55%

The figures show how the study area presents high average slopes and a discontinuous pedestrian network. The absence of pavements in most of the central streets is due to the historical and architectural characteristics of the city centre; in the outer areas, however, these are mainly peripheral streets, with portions of suburban streets. Just over 35 per cent of the study area has roads with an average gradient of less than 5 per cent.

The elements considered represent the basis on which the methodology described in the following section is applied.

3 Methodology

The proposed methodology is developed in three steps: demand (step one) and supply (steps two and three) characteristics.

Step one: The use of isochrones is used as a tool for evaluating and analyzing the accessibility of points within the network is documented in the literature, such as for LPT accessibility [19, 20]. In this study, the objective is to determine the accessibility of the pick-up point system by evaluating the pedo-national 5-min isochrony, following up on what was defined in the introductory section.

Consider the study area characterized by a number n = 1, 2, n…, S of zones, each characterized by an area An and a POPn population. Consider a network of pick-up points characterized by several points p = 1,2,…, P. Define ip as the area delimited by the 5-min pedestrian isochrony generated by point p.

For each area ip, it is possible to evaluate the area obtained by the intersection with the generic An; the intersection area is defined as An,p.However, for each area n, we consider the population POP_n uniformly distributed within the area. We denote by POPn,p the proportion of the POP_n population counted within the area $A_{n,p}$ and evaluate with:

$$POP_{n,p} = \frac{A_{n,p}}{A_n} POP_n \tag{1}$$

The total POP_l population within the IP area is obtained as:

$$POP_p = \sum_{n=1}^{S} POP_{n,p} \tag{2}$$

Step Two: The second step is related to the characterization of configurational space. Space syntax is used, identified as the set of techniques for the study and analysis of spatial configurations [21]. The basis of the space syntax is the axial map; the axis is an element that links one space with another.

The map can be disaggregated into segments at the intersections to improve the analysis' accuracy [22]. Among the measures of centrality identified by the space syntax, it is worth mentioning the To-movement measures, which identify the characteristics of a space as a potential destination [23]. In this sense, they represent an element to parameterize the accessibility of a segment on the network. All centrality measures are influenced by the geometric distance between the origin and destination space, expressed as the sum of angular deviations from an origin to a destination [24].

The measure used is the Normalized Angular Integration, NAIN, which is calculated with reason r = 300 m, i.e. the distance travelled in 5 min with an average speed of 1 m/s [25]. In this study, $NAIN_{r=300}$ m is evaluated for each segment, and the segment value on which it directly insists is considered for each point.

Third step: The third step is related to evaluating the characteristics of the pedestrian infrastructure. In this sense, the area on which the pick-up point is located is characterized by two elements. The first is an element that characterizes the orography of the terrain, i.e. the slope. It is emphasized that an excessive slope represents an important li-mite for different categories of users. The average slope of the segments belonging to that isochrone is evaluated for each isochrone. If L_p is the total length of the network intersected by the isochrone ip, and if L_p,s is the length of the network intersected by the isochrone with a slope belonging to a certain range, three indicators are adopted to assess the goodness of the slope of the area:

$$L\%_{p,s} = L_{p,s}/L_p, \tag{3}$$

It measures the proportion of the network with a given range slope present within the isochrone out of the whole network present. It is a parameter specific to each isochrone.

$$PEND_p = L_{p,s}/L_{TOT,5} \tag{4}$$

It measures the share of slope belonging to the given range present within the isochrone concerning the total analyzed network with an average slope belonging to the given range. It serves as a measure of the concentration, in a given isochrone, of acceptable pedestrian height.

$$PTOT_p = L_{p,s}/L_{TOT} \tag{5}$$

It measures the share of range slope present within the isochrone out of the total network present. The other element is the pedestrianization characteristics of the urban area. Five potential categories of axes are identified:

- footpath, a street arc in which there is pedestrian infrastructure in its own right of way, having width characteristics that allow for pedestrianization that is considered acceptable;
- pedestrian thoroughfare, an arc in which pedestrian-only traffic is interested;

- stairway, an arch in which the infrastructure is entirely stepped. It represents an advantage for the absence of promiscuity with vehicle traffic but is a limitation for the circulation of certain categories of users;
- deficient pavement, a road arch in which the pedestrian infrastructure has poor characteristics, has a narrow width. It does not qualify as a pedestrian street;
- absence of pedestrianization, an arch in which pedestrian transit in its own right of way is impossible.

The average slope of the segments making up the isochrone is evaluated for each isochrone. If L_p is the network's total length intersected by the isochrone i_p, and if $L_{p,w}$ is the network length intersected by the isochrone with good pedestrianization characteristics. Thus, three indicators are adopted to assess the goodness of pedestrianization in the area:

$$L\%_{p,w} = L_{p,w}/L_p, \tag{6}$$

It measures the share of acceptable pedestrianization present within the isochrone out of the total network present in the isochrone and is a parameter specific to each isochrone.

$$WALK_p = L_{p,w}/L_{TOT,w} \tag{7}$$

It measures the share of acceptable pedestrianization present within the isochrone compared to the total of the analyzed network with good pedestrianization characteristics. It measures the concentration of adequate pedestrian share in a given isochron.

$$WTOT_p = L_{p,w}/L_{TOT} \tag{8}$$

It measures the share of acceptable slope present within the isochrone out of the whole network. Hence, evaluating these three elements makes it possible to characterize the pick-up point in three complementary aspects, population, pedestrian infrastructure and configurational and geometric accessibility. Finally, at the end of the characterization, it is possible to make a quantitative judgement on the positioning of each of them. The results of the methodology described, applied to the case study presented in Sect. 2, are illustrated in Sect. 4.

4 Results

4.1 Application

This section illustrates the numerical results, following the approach described in Sect. 3.

First step. For the population study, reference was made to ISTAT data [26]. The study was limited to the census plots within the area. It is not a problem, since the peripheral parcels are not entirely contained in the area. Thus discarded areas have zero population and therefore do not influence the study. At each pick-up point, the isochronous was generated. Figure 6 shows an example of the i4 and i7 isochrones.

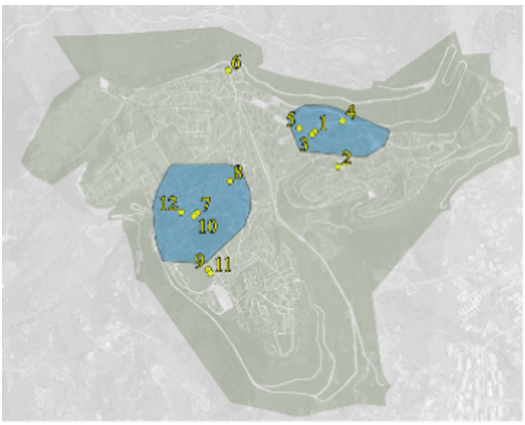

Fig. 6. Definition of Isochrones i_4 and i_7

Table 2. POPp values for each area p. Consider how POP_{TOT} refers to the union of the areas.

p	1	2	3	4	5	6	7	8	9	10	11	12	TOT
POP_p	1527	1856	1495	738	1594	1758	2418	2410	1786	2360	1547	1923	9113
$POP\%_p$	10%	12%	10%	5%	10%	12%	16%	16%	12%	15%	10%	13%	60%

Table 2 shows the characteristics of the population percentage covered by each pick-up point and the total percentage covered in 5 min by the ITOT area.

Each pick-up point has a good population coverage, always between 10% and 15% of the total, except for point 4. Overall, 5-min pedestrian accessibility is guaranteed for 60% of the resident population. The resident 40% is mainly located in the South and North-West areas, which are uncovered by pick-up points.

Second step. The configurational analysis returns the $NAIN_{r=300\,m}$ values mapped in Fig. 7. It is pertinent to note that the analysis was conducted by DepthmapX [27].

The NAIN value considered ranges from a minimum of 0.3 to a maximum of 3.74. Within the scenario considered, the results in terms of NAIN, and reference quartile, for each of the points considered are summarised in Table 3.

The result shows a significant finding: a high Integration value for each point considered. All the points, except p = 1,2,4, are positioned within the first quartile, among the segments characterized by greater accessibility; the others present high values. However, this is mainly due to the deep interconnection of the inner area of Enna.

Third step. Finally, the evaluation of the pedestrian areas within each isochrone is summarised in Table. 4.



Fig.7. $NAIN_{r=300\ m}$ for the study area

Table 3. $NAIN_{r=300\ m}$ and the respective reference quartile for each segment associated with the generic point p.

P	1	2	3	4	5	6	7	8	9	10	11	12
$NAIN_{r=300m}$	1,61	1,62	1,71	1,51	1,7	1,72	1,74	1,75	1,8	1,65	1,8	1,69
Quartile	2	2	1	2	1	1	1	1	1	1	1	1

Table 4. Summary of the indicators on the goodness of the pedestrianisation of the area related to the generic point p.

P	1	2	3	4	5	6	7	8	9	10	11	12	TOT
$WTOT_p$	3,4%	3,3%	3,5%	2,6%	3,5%	2,3%	3,5%	2,9%	3,4%	3,5%	3,2%	3,6%	15,5%
$L\%_{p,s}$	37,7%	29,6%	37,8%	44,8%	37,2%	24,4%	29,6%	26,4%	33,7%	29,7%	35,8%	33,5%	30,2%
$WALK_p$	13,3%	12,8%	13,4%	9,8%	13,4%	8,8%	13,6%	11%	13%	13,4%	12,4%	14%	59,5%
$STOT_p$	2,1%	2,4%	2,1%	1,9%	2,2%	3,7%	3,8%	3,8%	2,2%	3,6%	2%	3,7%	15,2%
$L\%_{p,s}$	22%	20,7%	22%	32,8%	22,6%	39,4%	31,7%	34,7%	22,1%	29,8%	22,5%	33,1%	29,5%
$SLOPE_p$	5,8%	6,7%	5,8%	5,4%	6,1%	10,2%	10,8%	10,7%	6,1%	10%	5,5%	10,3%	42,5%

The results show a pedestrianization characteristic of each area ranging between 20% and 40%, around an overall value of 30%. It should be noted that the arches with good pedestrianization characteristics and the entirely pedestrianized arches were only considered in the analysis. It excludes the stairs due to their characteristic, implying potential

difficulties for users with motor disabilities, older adults and users with pushchairs. Similar percentages are obtained for the evaluation of slopes. In general, point 4 presents the best value of pedestrianization. More than 44% of the total value of the network entirely contained in the isochrone is pedestrianized. The WTOT and WALK, PTOT and PEND measures allow the pedestrianization characteristics scaled over the entire network to be assessed.

Interestingly, the percentage of the pedestrian network contained in the isochrony is almost 60%, implying that activities tend to be concentrated in the walkable area. Only 40%, on the other hand, is the percentage of the network with an acceptable slope contained within the isochrone. 15% is the percentage of pedestrian and adequate slope network contained within the isochrone compared to the total road system in the study area.

5 Discussion and Conclusion

This research focuses on a current issue related to the increase in e-commerce and online sales that have prompted many people to purchase and pick up parcels at several pick-up points in urban areas. The research work, in particular, shows the preliminary definition of a methodology to evaluate the existing network of pick-up points by considering three different aspects, namely the geometric accessibility of the points in the network, population coverage and walkability characteristics of the area relative to the point. It made it possible to classify the points according to these criteria, obtaining an evaluation of both the pick-up point system and the characteristics of the built-up area.

The first significant element is undoubtedly related to the nature of the residential area. From a geometric point of view, the high accessibility values show the deeply interconnected nature of the built-up area of the case study. For this reason, the study of pedestrianization makes it possible to cover the aspect related to the characteristics of the infrastructure instead. Although geometrically accessible, the built-up area presents adverse pedestrianization characteristics discouraging the use of the point. It occurs although most points are located in the most central built-up area. Consequently, despite the good overall coverage in terms of population (approx. 60% of the total), users may not be encouraged to use the points, even if they reside within the theoretical 5-min pedestrian zone.

This work may suggest network evaluation criteria for delivery companies to optimize distribution strategies, considering the urban reality in which distribution occurs. On the other hand, it may help public administrators and planners to have quantitative elements to support traffic and pedestrian flow analyses.

Other future developments are possible. Possibilities include evaluating residents' actual use of these points within the studied centre. On the other hand, the chance of developing a methodology that, starting from the basis described in this article, can provide decision-supporting tools for positioning a new pick-up point, considering the already existing network.

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Freight Distribution in Urban Area: Estimating the Impact of Commercial Vehicles on Traffic Congestion

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Abstract. Urban freight transport plays an important role in the sustainability of the cities, as it is the last-leg of the supply chain which connect the production activities, generally located outside, to both commercial activities and final consumers, located inside the city. The problem that arises is related to the estimation of impact that the commercial vehicles determines on traffic congestion, and more generally on the liveability of urban areas. Current methods use the passenger car equivalent coefficients to convert heterogeneous traffic into homogeneous one in which it is assumed that only cars are travelling, according to different criteria based on road and vehicles characteristics, and traffic composition. The paper introduces a criterion of conversion of commercial vehicles based on the freight capacity, according to the potential impact of the vehicle when executing the freight delivery operations inside urban areas. This problem is further amplified in urban areas where there is a lack of material and immaterial infrastructures able to support city logistics operations, as in the case study examined.

Keywords: Sustainable development · city logistics · freight vehicles · car equivalent coefficients · case study

1 Introduction

Cities are moving nowadays towards a low-carbon transport and several measures allowing to increase people walking, cycling, using transit and vehicles powered by alternative fuels have been introduced in order to reach sustainable development goals [1, 2].

Urban freight transport plays an important role in the sustainability of the cities; however, it has negative externalities in terms of environmental, economic and social issues [3, 4]. It is worth noting that freight vehicles travelling inside urban areas have increased considerably in recent years due to changes in retailers' patterns (e.g., reduction/elimination of stocks, just-in-time) and in citizens' habits (e.g., e-commerce) (see [5, 6]).

Several city logistics measures have been promoted and implemented by cities during the last two decades [7, 8]. They are commonly grouped into four categories: *governance*, such as delivery-pick up time windows, road pricing; *equipment*, related to loading units

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(new standards) or transport units (e.g. vehicles); *immaterial infrastructures*, involving research, training and emerging ICT; *material infrastructures*, such as roads and lanes (i.e. reserved to freight vehicles), and dedicated areas (i.e. for loading/unloading operations, urban distribution centres).

City logistics measure should be identified inside a circular process that considers three interconnected elements: city planning theories, city policies and rules and city development, [9]. In order to achieve the convergence among the above elements, city planning theories should be materialized into city policies and rules in order to implement city development, on one side; city development should influence policies and rules that should match city planning theories, on the other side.

In the above circular process, the role of regional administrations is important in accompanying municipalities along the path from planning theories to policies and rules. In the literature a relevant experience comes from Calabria regional administration, which provided financial resources, scientific and technical support inside a public engagement approach with city decision makers and society [10–12].

The ex-ante performance and impacts generated by city logistics measures could be evaluated by means of Transport System Models (TSMs) [13, 14], which are able to reproduce the process of urban distribution of freight to commercial activities and final consumers. TSMs for urban freight distribution have been developed since the end of the 90s, when the first city logistics experiences were carried out in some Northern European cities. The existing literature covers different elements of the urban freight distribution process: the representation of the last-mile distribution chain and the role of the emerging ICT technologies [15], on the supply side; and the simulation of stakeholders' behaviour and interactions, on the demand side. Detailed literature reviews are reported in [16–19].

The problem that arises is related to the impact that city logistics determines in terms of commercial vehicle flows, and more generally on the liveability of urban areas. Current methods use the "passenger car equivalent" coefficients to convert heterogeneous traffic into homogeneous one, according to different criteria related to road and vehicles characteristics, and traffic composition. In the literature many works have studied the load determined by commercial vehicles and various models have been developed in the last 20 years that allow to simulate the movements of vehicles in highly congested urban areas [20, 21]. There is a lack in the literature concerning the study of city logistics impacts in regions where the socio-economic development levels are lower than more developed regions and where material and immaterial infrastructures that support city logistics operations are scarcely present. That is, it is necessary to verify what is the impact on the urban transport system in territories where these two characteristics are present. The answer to this question is particularly important, in order to arrive to theoretical hypotheses on which appropriate city logistics measures depend.

The paper introduces a criterion to convert commercial vehicles into equivalent passenger cars based on the freight capacity, given the high impact of these vehicles on traffic congestion when executing the freight delivery operations inside urban areas. This problem is further amplified in urban areas where there is a lack of material and immaterial infrastructures able to support city logistics operations (e.g. parking, loading and unloading operations), as in the case study examined.

The method used in the paper consists in the decomposition of the problem into two parts. In a first part, the overall traffic that affects a territory that has the two characteristics identified above is studied, highlighting the presence of commercial vehicles inside vehicular traffic flow. In the second part, the classification of commercial vehicles is studied by specifying different classes in terms of freight capacity. On this basis, conversion factors have been estimated, uniquely and schematically determined by the capacity of the commercial vehicles. It is therefore possible to go back to private cars in order to verify the impact to traffic provided by commercial vehicles, which are converted into equivalent cars.

It is important to note that the surveys reported in this paper refer to a pre-Covid time period, as Covid has implied a further increase in commercial vehicles due to a relevant increase of e-commerce [22].

The paper reports a description of a survey carried out in a small-size city related to freight vehicles entering in the central area in order to estimate their impact on the vehicular traffic. To this end, the indicators for estimating the coefficients of equivalence of commercial vehicles are presented in Sect. 2. Section 3 describes a specific survey, on freight vehicles entering in the central area of a small-size city and the estimation of the incidence of equivalent freight vehicles respect to the vehicular traffic flow. The conclusions and the further research are presented in the last section.

The results obtained are particularly significant because they highlight a decisive theme for urban areas. In this sense, the paper is important for technicians and decision-makers of public administrations, because it remarks the need to intervene even in areas that are not particularly rich and densely populated. It is also important for researchers because it requires the development of appropriate intervention models.

2 Vehicular Traffic in Urban Area: Incidence of Freight Vehicles

Vehicular traffic in urban area is composed by different classes of vehicles. Road vehicles for people mobility differ in the dimension and passenger's occupancy rate. Road vehicles for freight mobility differ in the capacity in terms of maximum volume and weight that can be transported. In relation to city logistics, vehicles can be used for distribution and delivery of different categories of freight (food, wastes, medicines, fuel delivery, raw materials for production processes, etc.).

Current methods [23, 24] use the passenger car equivalent coefficients to convert heterogeneous traffic into homogeneous one in which it is assumed that only cars are travelling, according to different criteria related to road and vehicles characteristics, and to traffic composition. They are important in the field of traffic engineering for supporting capacity analysis in road links and saturation flow rates at road intersections, and in general in the network.

Urban freight distribution processes have a relevant role for the cities. The pandemic emergency connected to COVID-19 produced transformations and uncertainties in the transport and logistics sector, especially in the recovery period. Users' purchasing habits have changed and e-commerce has begun to have an increasingly important role. The growing use of logistics services has produced an increase in the number of vehicles that delivery goods in urban areas. These changes have direct effects on urban transport systems.

It is therefore necessary to understand the urban logistics systems by increasing knowledge of the phenomenon in order to identify solutions suitable for the urban context.

In this paper, in order to contribute to the understanding of the urban freight transport phenomenon, the road vehicles flows crossing a generic road section (i) are grouped in the following classes:

- passenger (p) vehicles' class:
  - p0: bike or vehicles for micro-mobility, indicated as $f_{i,p0}$;
  - p1: motorcycle, indicated as $f_{i,p1}$;
  - p2: cars, indicated as $f_{i,p2}$;
  - p3: bus, indicated as $f_{i,p3}$;
- freight (f) vehicles' class:
  - f0: including vehicles with a capacity C > 18000 indicated as $f_{i,f0}$;
  - f1: ultra heavy (UL) vehicles, including vehicles with a capacity (C) comprises in the interval 3600 < C < 18000 indicated as $f_{i,f1}$;
  - f2: heavy (H) vehicles, including vehicles with a capacity (C) comprises in the interval 1600 < C < 3600 kg, indicated as $f_{i,f2}$;
  - f3: light (L) vehicles, including vehicles with a capacity comprises in the interval 1000 < C < 1600 kg, indicated as $f_{i,f3}$;
  - f4: ultra light (UL) vehicles, including vehicles with a capacity (C) comprises in the interval C < 1000 kg, indicated as $f_{i,f4}$.

In order to measure the incidence of road freight vehicles in section (i), the following indicator is introduced:

$$a_{i,f} = \sum_{k=0,\ldots4} f_{i,fk} / \sum_{k=2,3} f_{i,pk} \tag{1}$$

The indicator is expressed in terms of a ratio between all freight vehicles (class f) and the sum of auto and buses dedicated to people mobility (classes p = 2, 3).

The equivalent road vehicle flow, $f_{i,p*}$, in section (i) is expressed as:

$$f_{i,p*} = \sum_{k=2,3} f_{i,pk} + \sum_{k=0,\ldots4} E_{fk} \cdot f_{i,fk} \tag{2}$$

where E_{fk} is the passenger car equivalent coefficient of freight vehicles of class fk.

3 Case Study

The study area is part of the municipality of Reggio Calabria (180 000 inhabitants and an extension of 236.02 km^2) and consists of a central district with mixed residential and retail activities and clustered educational and public services; and of suburban districts with manufacturing activities and scattered residences (Fig. 1).

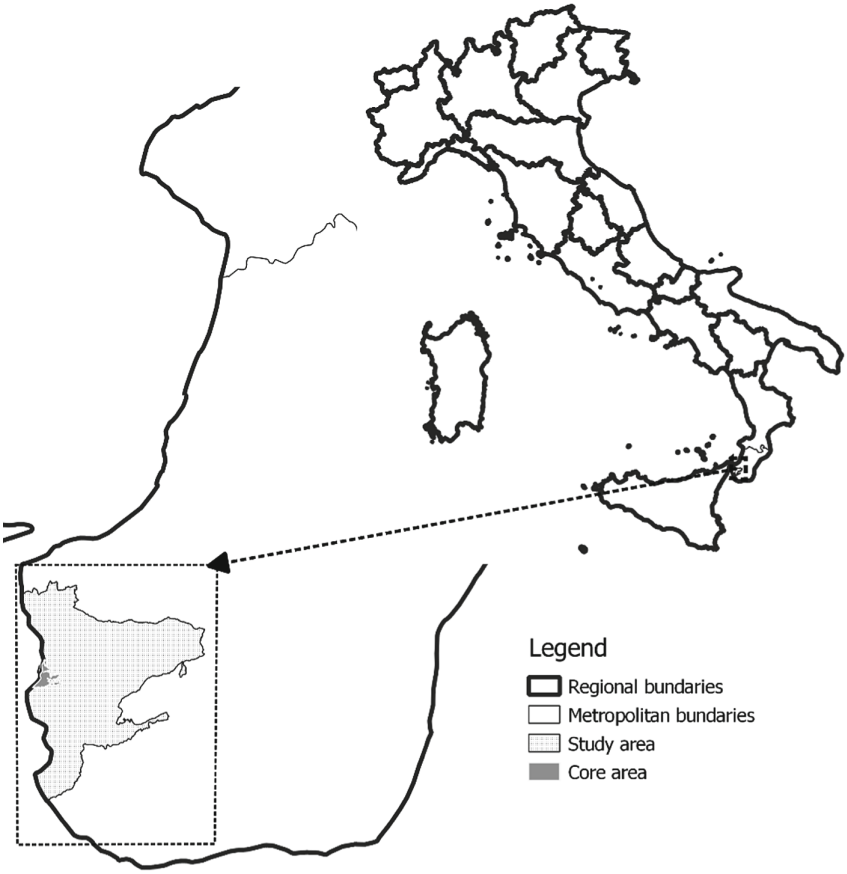

Fig. 1. Study area (a) and portion of the central district with zones (b). (Source: elaborated by authors)

3.1 Indicators for Road Vehicles

The examined city has road infrastructures of primary and secondary relevance. The primary connection is the A2 motorway, also known as "Mediterranean or Salerno-Reggio Calabria". This road connects Campania, Basilicata and Calabria regions, representing one of the main national axes. Others relevant roads are: the SS 106 Jonica that connects Calabria, Basilicata and part of the Puglia regions; the road SS18 Tirrena Inferiore that is one of the most important and longest arterial roads in Southern Italy.

Part of the recalled roads cross the study area of Reggio Calabria (see Fig. 2).

Different vehicular road traffic surveys were realized in the city to analyze the mobility of people and goods. The results supported the urban transport planning process, and in particular the Sustainable Urban Mobility Plan (SUMP) referred to the municipal area, adopted in 2017 [25]. With this aim, some surveys are conducted for updating the traffic database with road vehicular flows relative to the municipal area. A survey was conducted on vehicular flows crossing a subset of road sections. The sections are located

within the urban center (core sections) and at their boundary (cordon sections). The data presented in Table 1 concern the cordon sections.

The traffic counts in the road sections are collected in three time periods of a typical working day (07:00 – 09:00; 12:30 – 14:30; 17:00 – 19:00).

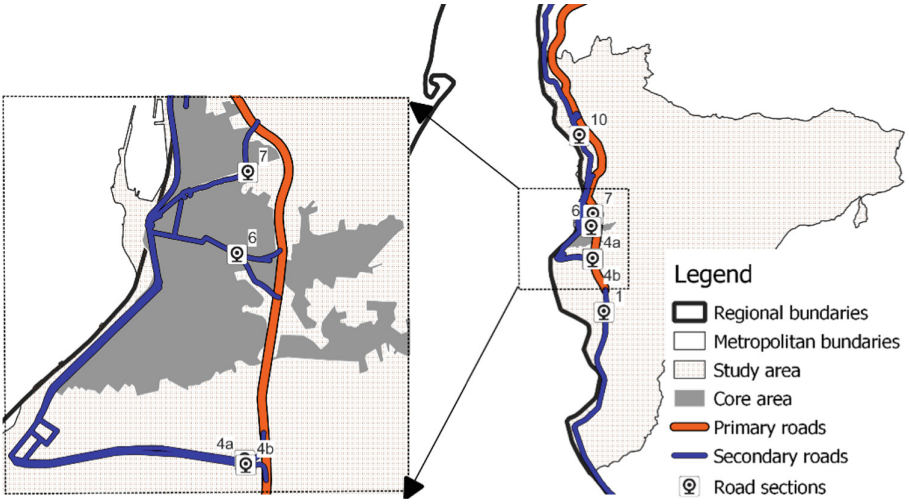

Fig. 2. Location of the selected road core sections. (Source: elaborated by authors)

Table 1. Traffic counts in the road sections in the periods 7:00–09:00, 12:30–14:30, 17:00–19:00.

		People vehicles		Freight vehicles			Indicator	
		Car	bus	UL+L	H	UH		
	Name	$f_{i,p2}$	$f_{i,p3}$	$f_{i,f}+f_{i,f3}$	$f_{i,f2}$	$f_{i,f1}+f_{i,f0}$	$\alpha_{i,f}$	
North(N)	10-SS18 Archi	7208	59	290	174	22	6.7%	4.6%
	7-Via Lia	7788	29	201	107	1	4.0%	
	6-Via Cardinale P.	7759	39	241	60	1	3.9%	
	4b-Cedir	10458	44	323	111	10	4.2%	
South(S)	4a-Cedir	10075	58	393	133	7	5.3%	6.4%
	1-Saracinello	5224	70	346	95	7	8.5%	
Total		48512	299	1794	680	48	4.5%	5.5%

UL: Ultra Light; L: Light; H:Heavy; UH: Ultra Heavy
(Source: Elaborations from [25])

3.2 Indicators for freight vehicles

The commercial vehicle fleet has been subdivided into classes according to the load capacity. Five classes of freight vehicles have been identified. Table 2 shows a range

of load capacity associated with each class of commercial vehicles and the average conversion equivalence coefficient calculated assuming the Fiat Panda Van as equivalent vehicle with a load capacity of 550 kg. For each of the five classes considered, an average equivalence coefficient was assumed equal to the coefficient calculated respect to the freight vehicles in the market belonging to each class.

Table 2. Freight vehicles: classes of capacity and equivalent conversion coefficients

Class	Capacity, C [kg]	Equivalence coefficient
0	C>18000	54.5
1	3600 < C < 18000	24.5
2	1600 < C < 3600	4.0
3	1000 < C < 1600	2.4
4	C < 1000	1.4

Freight vehicles entering inside the study area in the peak period (7:00 am – 9:00 am) of a working day have been counted and classified according to the five classes defined. The observation includes freight vehicles delivering perishable food, building materials, materials for maintenance and services and other durable goods.

The road sections that are the gate for entering inside the city are grouped according to two geographic areas:

- *Southern gates*, vehicles entering in the city from the following road sections: 106 Jonica (SS 106): 1-Saracinello, 2-Arangea, 3a-Modena Sud, 3b-Modena Nord, 4-Cedir, 5a-Spirito Santo Sud;
- *Northern gates*, vehicles entering in the city from the following road sections: 18 Tirrena Inferiore, 5b-Spirito Santo Nord, 6a-Via Petrara, 6b-Via Cardinale Portanova, 7-Via Lia, 8-Via Esperia, 9-Via Genoese Zerbi, 10-SS18 Archi.

Table 3 shows the flows of freight vehicles subdivided into the five classes according to their load capacity. It should be noted that it was not possible to identify the freight transported of the vehicles crossing the road sections considered, therefore the data reported may not be exhaustive. It emerged from the survey that, in the period considered, 400 commercial vehicles entered inside the city from the Southern gates, and 229 commercial vehicles entered inside the city from the Northern gates. The total number of entering vehicles was 629.

Figure 3 reports the frequencies of flow percentages of freight vehicles per each class entering inside the city trough the Northern gates, the Southern gates and the total vehicles entering inside the city. It is worth noting that class 4 of freight vehicles has the highest percentages (ranging from 42.0% to 33.0%), while class 1, 2 and 3 of freight vehicles have similar percentages (ranging from 25.0% to 14.0%), the lowest percentage belong to freight vehicles of class 0.

Table 3. Flow of freight vehicles per class in each road section

Road section	0 [veih/2h]	1 [veih/2h]	2 [veih/2h]	3 [veih/2h]	4 [veih/2h]	Total [veih/2h]
1-Saracinello	5	17	9	9	21	**61**
2-Arangea	0	7	5	12	19	**43**
3a-Modena Sud	0	12	9	6	34	**61**
3b-Modena Nord	6	4	3	12	9	**34**
4-Cedir	1	26	30	21	52	**130**
5a-Spirito Santo Sud	0	15	9	11	36	**71**
Southern road sections	**12**	**81**	**65**	**71**	**171**	**400**
5b-Spirito Santo Nord	0	8	10	6	6	**30**
6a-Via Petrara	0	1	9	20	11	**41**
6b-Via Cardinale Portanova	0	5	8	2	29	**44**
7-Via Lia	0	10	6	4	16	**36**
8-Via Esperia	1	3	12	5	0	**21**
9-Via Genoese Zerbi	0	2	8	6	8	**24**
10-SS18 Archi	0	16	4	6	7	**33**
Northern road sections	**1**	**45**	**57**	**49**	**77**	**229**
Total	**13**	**126**	**122**	**120**	**248**	**629**

Figure 4 reports the frequencies of standard deviation (s.d.) of flow freight vehicles per each class entering inside the city among the Northern gates, the Southern gates and the total gates. It is worth noting that the classes 1, 2, 3 and 4 of freight vehicles have similar values of s.d. (ranging from 5,0% to 15,0%), the s.d. among the Northern gates presents the highest values.

Table 4 reports the flow of equivalent freight vehicles for each class and for each road section considered. These values are obtained by multiplying the values of flow in Table 3 for the values of equivalent conversion coefficients per class of Table 2.

Table 5 reports the value of incidence of freight vehicles respect to passenger vehicles calculated from eq.1 considering equivalent freight vehicles for each class. It is worth noting that the value of the indicator increases to 30.40% respect to the value calculated with the freight vehicle counted (5.5%) reported in Table 2.

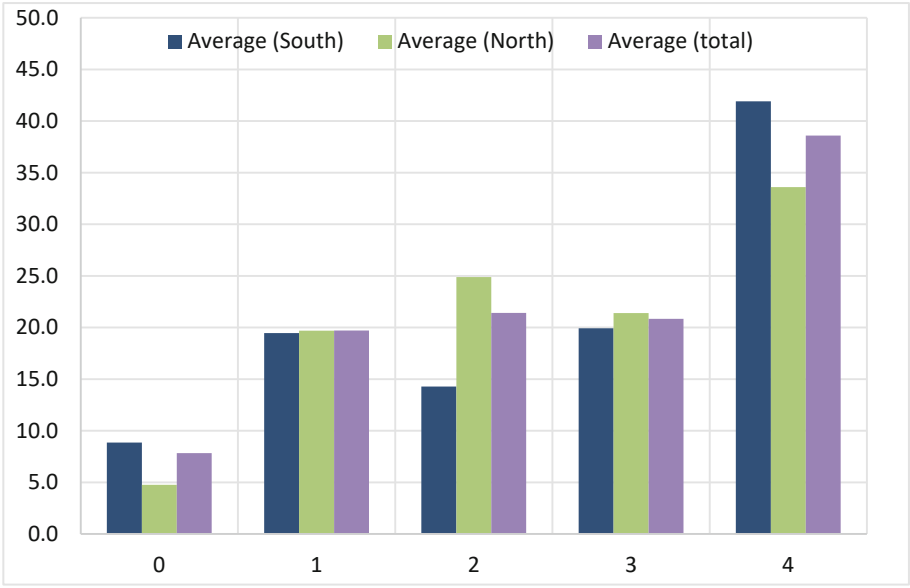

Fig. 3. Observed percentages of freight vehicle class: average values

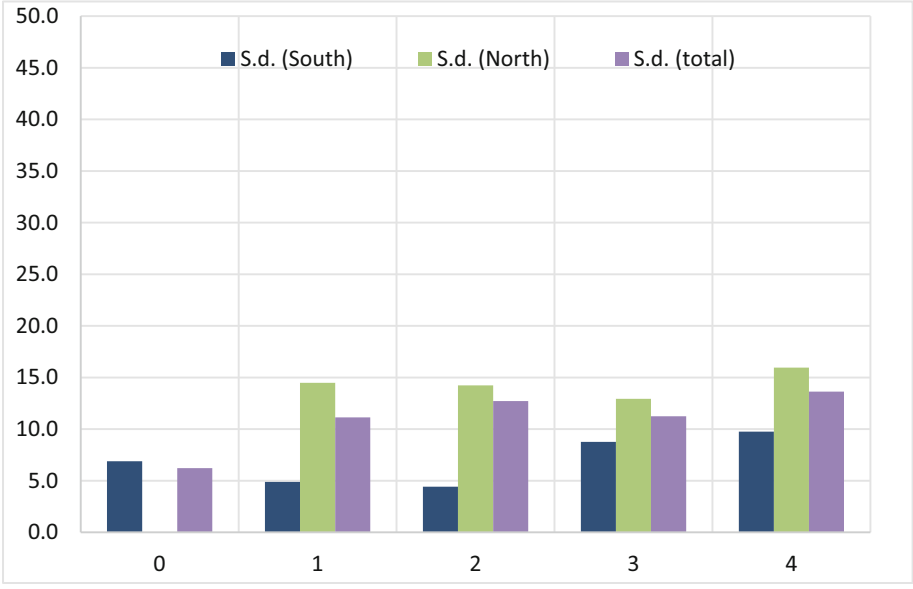

Fig. 4. Observed percentages of freight vehicle class: standard deviation (s.d.) values.

Table 4. Flow of equivalent freight vehicles per class in each road section

	0	1	2	3	4	Total
Road section	[veih/2h]	[veih/2h]	[veih/2h]	[veih/2h]	[veih/2h]	[veih/2h]
1-Saracinello	273	418	36	22	30	**779**
2-Arangea	0	172	20	29	27	**248**
3a-Modena Sud	0	295	36	15	48	**394**
3b-Modena Nord	327	98	12	29	13	**480**
4-Cedir	55	640	122	51	73	**940**
5a-Spirito Santo Sud	0	369	36	27	51	**483**
Total road sections (South)	**655**	**1993**	**263**	**173**	**241**	**3324**
5b-Spirito Santo Nord	0	197	41	15	8	**260**
6a-Via Petrara	0	25	36	49	16	**125**
6b-Via Cardinale Portanova	0	123	32	5	41	**201**
7-Via Lia	0	246	24	10	23	**303**
8-Via Esperia	55	74	49	12	0	**189**
9-Via Genoese Zerbi	0	49	32	15	11	**107**
10-SS18 Archi	0	394	16	15	10	**434**
Total road sections (North)	**55**	**1107**	**231**	**119**	**109**	**1620**
Total	**709**	**3100**	**494**	**292**	**350**	**4944**

Table 5. Incidence of equivalent freight vehicles respect to passenger vehicles. Period 7:00-9:00 a.m.

	Passenger vehicles	Equivalent freight vehicles					Indicator
	$fp1+f_{p2}$	f_{f0}	f_{f1}	f_{f2}	f_{f3}	f_{f4}	(eq.1)
Total	16270	710	3100	494	292	350	30,40%

4 Conclusions

Urban freight transport plays an important role in the sustainability of the cities, as it is the last-leg of the supply chain which connect the production activities, generally located outside, to both commercial activities and final consumers, located inside the city. The estimation of impact that the commercial vehicles determine on traffic congestion, and more generally on the liveability of urban areas, is underestimated and not adequately

studied in the literature. Current methods use the passenger car equivalent coefficients to convert heterogeneous traffic into homogeneous one in which it is assumed that only cars are travelling, based on road and vehicles characteristics, and traffic composition. The idea proposed in the paper is to introduce a criterion of conversion of commercial vehicles into a "reference" commercial vehicle based on freight capacity, given that the impact of commercial vehicles when executing the freight delivery operations inside urban areas increase with their load capacity.

This problem is further amplified in urban areas where there is a lack of material and immaterial infrastructures able to support city logistics operations, as in the case study examined. The case study refers to a small city, located in the South of Italy, where no material and immaterial infrastructures able to support city logistics operations have been implemented. The results show that value of incidence of freight vehicles respect to passenger vehicles calculated considering equivalent freight vehicles for each class is double respect to the value calculated with the counted freight vehicles.

Further developments concern the calibration of the proposed conversion coefficients of freight vehicles according to experimental data, regarding the amount and type of freight transported by commercial vehicles entering inside the city, the number and type of destinations to be served (commercial activities vs. final consumers), the presence and the level of city logistics measures implemented, and other potential attributes.

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The Role of City Logistics in Pursuing the Goals of Agenda 2030

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Abstract. The issue of city logistics has historically been addressed as a problem for improving the generalized efficiency of the delivery routes under different operating conditions. The remarkable development of supplies for purchases in store and on line has posed different problems for the society in terms of the impacts produced. On the other hand, there is a growing and worldwide interest in preserving the environment where people live, which addressed the definition of Sustainable Development Goals of Agenda 2030. Therefore, today the central question is how to create a city logistics that allows us to pursue the objectives of Agenda 2030. The method to be used should analyze the goals, targets, and indicators of Agenda 2030, and subsequently, it should verify which current methodological design tools allow us to estimate the improvement of city sustainability, measured through the changes of a set of proposed indicators. On this basis, the indicators proposed are aggregated into three classes, which are related to: direct, indirect and conditioned impacts. The result obtained is thus the identification of the targets of Agenda 2030 that can be pursued by city logistics and therefore the need for researchers to change the focus moving from the only targets defined by the efficiency of the delivery routes towards the targets introduced by Agenda 2030. Such a work opens the way for new approaches to deal with the implementation of city logistics.

Keywords: City logistics · Agenda 2030 · Sustainable development goals · City sustainability · City livability

1 Introduction

Cities are particular complex systems in relation to the high concentration of population and therefore of human activities of various kinds, i.e., moving from residence toward work, leisure, and the health. This concentration of population and of these activities requires more and more goods available and therefore there is the need to manage the supply chains both of the traditional sale channels at stores, and of the new channels connected with the on-line sales. For example, in the United States, in just one year from 2009 to 2010, e-commerce sales increased by 14%. Total e-commerce sales for 2022, always in USA, were estimated at $1,034.1 billion, an increase of 7.7% from 2021, and

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has been accounted for 14.6% of total sales. In Europe, 74% of internet users bought or ordered goods for private use in 2021 [1, 2]. End users have changed their behavior and purchasing decisions over time, gradually moving from traditional distribution channels to new ones.

The increase in mobility is statistically connected with the growth of the Gross Domestic Product (GDP) per capita in the area and with collective well-being. As mobility grows, the economic and social levels of cities raise. But at the same time, the increased mobility is one of the most important elements that causes the increase of the environmental impact, both for carbon footprint and for fine particles. In fact, emissions that produce effects on the environment can be traced back to two categories: those that cause global warming and therefore the effects are at a planetary level; those that directly affect citizens and therefore the effects are only at urban level. To have an order of magnitude, consider that road transport is responsible for 95% of CO_2 emissions in the transport sector in the EU (682 million of the total 712 million tons) [3]; PM_{10} causes various types of disorders and affects the mortality rate (e.g., in Switzerland, around 25% of PM_x air pollution derives from vehicles [4].

The study of city logistics has evolved over time considering mainly the component of cost optimization, considering the most advanced telematics application [5–8] in line with what has historically been developed for the logistics of companies in the relationship between manufacturers and distributors. Other components such as social and environmental ones have not been deepened. Freight mobility is a decisive component of overall urban mobility, and in particular of the last mile [9]. This centrality implies significant economic, social and environmental impacts, and therefore an important role in the development of the cities themselves.

Economic, social, and environmental impacts are the cornerstones of sustainable development strategies, as defined by the Brundtland report [10]. The 1987 UN report introduced social and economic problems into sustainable development, whereas previously sustainability was assessed only against environmental issues. The Brundtland report has launched a wide-ranging debate at the international level among countries with different levels of development. Environmental issues were greatly explored at the Rio conferences and then in the Kyoto agreements.

The path of international sharing of the fundamental principles of sustainable development had its moment of synthesis with the drafting and signing of Agenda 2030 document by the majority of UN countries [11].

The European Commission (EC), in line with the indications of Agenda 2030, has formalized the idea of sustainable urban mobility by issuing guidelines to prepare sustainable urban mobility plans [12]. The 2019 guidelines follow the first-edition guidelines of 2013 and previous work supported by the EC particularly important, among which the ENCLOSE project can be recalled [13] in which the guidelines for sustainable urban logistics plans (SULP) were defined.

The question that this note wants to address concerns whether the organization of urban freight traffic of the last mile can contribute to pursuing the goals of Agenda 2030, and specifically to which objectives. Therefore, we want to go beyond the traditional approach implemented daily by everyone, which considers the last mile, and the logistics connected to it, only in terms of cost efficiency. On the other hand, the sustainability

approach appears to be only theoretical. The problem also in this case, as in other dimensions of planning, is to find a synthesis among the theories of urban development, the urban rules, and the development of real implementations [14]. The dynamics among theories, rules and implementations is a particularly important path for the best evolution of city logistics [15].

To address the issues introduced earlier, Session 2 presents the structure of Agenda 2030 with the goals, targets, and indicators, recalling some main aggregations of objectives. Session 3 discusses the role of city logistics with respect to the various goals of Agenda 2030, and the related targets and indicators. In the last section, conclusions are drawn, and lines of further development are indicated.

The proposed work could be useful to decision makers and planners at the national level because it should allow them to organize general measures and possible economic support in the correct directions. It is also useful at the local level because it allows political decision makers and public technicians to implement the best sustainable solutions for the organization of urban traffic. It is also useful for the management of private transport and logistics companies because it allows to plan and program business development in line with the Agenda 2030. Finally, it is useful for researchers who deal with all the problems related to the efficiency of the delivery paths because they can give a turning point to their work by introducing, in addition to the consolidated attention paid to cost efficiency, a specific and greater attention to the sustainable development.

2 The Structure of Agenda 2030

The path taken by the United Nations (UN) since its establishment to define conditions of peace and prosperity for all the peoples of the Earth has been particularly complex. The work has always been based on a careful analysis of the phenomena. In this analysis, it has been estimated that by 2050, 66% of the world's population will live in cities. The problem of better management of cities thus becomes one of the main problems of sustainable development. If cities will not organize themselves properly, the Sustainable Development Goals cannot be pursued [16, 17].

The UN in 2015 proposes a particularly relevant document which specifies the objectives to be pursued by 2030 to aim at sustainable development of the whole planet. The document is signed by 193 countries, which undertake to adopt it for the development of national policies in the various sectors. The overall objective of the document is "peace and prosperity for people and the planet, now and in the future." [16, 18].

The basic structure of the Agenda 2030 consists of 17 general goals that must be pursued (Fig. 1). To make it possible, it needs to identify specific quantitative analyses that allow to verify the level of progress of the sustainability policies of the single countries. In 2018, the UN developed a specific document, in which, each goal is divided into specific targets, which, in turn, are disaggregated into one or more indicators that indicate the status of each goal in the generic year. Against the 17 Sustainable Development Goals (SDGs), 189 targets and 261 indicators are specified [19].

On the basis of the 261 indicators, each country must prepare an annual review of its situation. To this end, each country shall prepare the collection of adequate national statistics in order to allow the progress of specific policies to be compared. Analysis

of national statistics shows that not all UN indicators are currently recorded. Individual countries can match a UN indicator with one or more indicators if the UN indicator is not in the national collected statistics. In some cases, a UN indicator may not correspond to any indicator.

The lack of adequate national statistics is a serious limitation to the possibility of verifying what is happening in single countries. To overcome this limit, in the context of goal 17th, it is expressly indicated as a target the development of adequate national statistics. The 17 SDGs refer to different fields of human activity. However, it is possible to identify two homogeneous groups that can be considered reference for all countries [20, 21]. A first group can be defined as "*vital needs*". In the sense that they are the primary objectives for a society. It is no coincidence that the group of vital needs is composed of the first three SDGs that refer to poverty, hunger, and health.

The second group is more complex to homogenize but can be synthesized into "*optimal needs*". In the sense that once the objectives of the first group have been addressed and resolved, those of the second group constitute in some way the main guidelines for the development of society. They can be summarized with the key words: education, equity, health, and water for all.



Fig. 1. The Sustainable Development Goals related to human activity [18]

Even with the necessary distinctions, it is as if a sequential reading could be proposed, translating Maslow's pyramid from individual to society [22, 23]. It is emphasized that Agenda 2030 in the public version does not provide for any hierarchy in the objectives and relative targets, but a detailed reading allows the two clusters of objectives and indicators previously defined to be identified.

3 Agenda 2030 and City Logistics Measures

3.1 Types of Goals

The measures implemented to organize city logistics have significant impacts on the pursuit of the goals and targets of Agenda 2030 [13, 24]. As part of the city logistics measures, both those that transport and logistics operators daily take to deliver their goods and those that the public administration (at the different levels and branches) takes to organize the overall flows of goods vehicles produced by the various operators must be considered [25].

It is possible to control the flows of freight vehicles in urban areas, in order to verify ex ante the results of planned measures, through appropriate Transport Systems Models (TSM). For the formalization of the TSM equations, one can refer to specific literature [26, 27].

The results of the TSM can in turn be considered the inputs for other types of models that allow one to measure impacts of other types.

Environmental impacts can be specified for each link of the network:

$$\boldsymbol{e}_{\mathrm{i}}^{*} = \mathrm{e_i}(\boldsymbol{f}, \boldsymbol{\lambda}) = \mathrm{e_i}(\boldsymbol{\Delta} \times \boldsymbol{h}, \boldsymbol{\lambda}) \tag{1}$$

where:

- $\mathbf{e}_{\mathrm{i}}^{*}$ is the impact value vector;
- $\mathbf{e}_{\mathrm{i}}$ is the impact function vector;
- $\mathbf{f}$ is the link flows vector;
- $\mathbf{h}$ is the path flow vector;
- $\boldsymbol{\Delta}$ is the link–path incidence matrix;
- $\boldsymbol{\lambda}$ is the set of physical and functional parameters.

Similarly, social impacts, $\boldsymbol{s}_i$, and economic impacts, $\boldsymbol{g}_i$, can be estimated. Given these general premises, the results deriving from the TSM in terms of $\boldsymbol{f}$, and the results deriving from subsequent models, in terms of $\boldsymbol{e}_i$, $\boldsymbol{s}_i$ and $\boldsymbol{g}_i$, allow to evaluate ex ante the modifications of the indicators of Agenda 2030 based on the measures implemented.

It is possible to consider the different SDGs and related indicators in relation to their degree of connection to Agenda 2030.

Figure 2 shows the three groups of SDGs whose indicators are influenced by city logistics measures [20, 28], also considering the e-commerce logistics [29]. The three groups have the following characteristics:

- they provide a *direct impact* on sustainable development measurable through the outputs of the TSM equations alone, by intervening directly on one or more indicators;
- they provide an *indirect impact*; the impact of the measures must be quantified with a second level of technics (formalized by models) that use the results of the TSM as input and implies choices that belong to different sectors of the same public administration (at the different levels and branches).
- they provide a *conditioned impact*, the impact of the measures can be quantified with the TSM models, or with the subsequent models, but using choices made in other contexts, not dependent on the same public administration (at the different levels and branches).



Fig. 2. The Sustainable Development Goals related to city logistics [18]

3.2 Direct Impacts

The targets directly influenced by interventions in city logistics are those concerning SDG 3 and SDG 11 (Table 1). As mentioned above, SDG 3 is one of the fundamental SDGs for sustainable development.

With regard to the direct impact of city logistics, it is worth noting the heavy role that freight vehicles play in road accidents (target 3.6.1), with the probability of more serious effects in the people involved, as well as in the production of air pollution (target 3.9.1).

SDG 11 is strictly related to urban and city communities. Its main focus is thus on passenger mobility and in particular:

- target 11.2, the adoption of specific practices for the optimal location of pickup points helps passenger accessibility;
- target 11.3 is particularly important because it requires the participation of citizens in planning choices and therefore in public choices on city logistics;
- target 11.6 is central because it introduces the environmental problem directly into the SDG of cities. It is useful to note that 11.6 can also be considered in the second group because it implies the need for other technical components to measure the output that affect it.

3.3 Conditioned Impacts

This group must include the SDGs to which city logistics can contribute, but whose results are conditioned by choices of other public administrations The SDGs to consider are: 7, 13 and 17 (Table 2). In fact, SDG 17 must also be considered because it aims. SDG 7, related to energy components, can be considered in various targets and indicators. It immediately emerges that the policies of local authorities can also impose different energy mixes or the use of renewable sources, this depends on the availability of network operators to supply energy from renewable sources in that place. Consider that modest

quantities can be produced with photovoltaic panels or other renewable sources, and these quantities can support the use of urban distribution centers, but certainly not the used vehicles. The evolution of the industrial energy sector strongly conditions the pursuit of goals by means of city logistics.

Table 1. Direct impacts: targets and indicators related to city logistics (based on [19])

SDG	Goals and targets	Indicators
SDG 3 – Good health and well-being	3.6 By 2020, halve the number of global deaths and injuries from road traffic accidents	3.6.1 Death rate due to road traffic injuries
	3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination	3.9.1 Mortality rate attributed to household and ambient air pollution
SDG 11 – Sustainable cities and communities	11.2 By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, people with disabilities and older persons	11.2.1 Proportion of population that has convenient access to public transport, by sex, age, and persons with disabilities
	11.3 By 2030, improve inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries	11.3.2 Proportion of cities with a direct participation structure of civil society in urban planning and management that operate regularly and democratically
	11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management	11.6.2 Annual mean levels of fine particulate matter (e.g. $PM_{2.5}$ and PM_{10}) in cities (population weighted)

SDG 13 is the one that collects the history of all environmental impacts. The main reference is to 13.2 and therefore to the carbon footprint. Consider that within the framework of 13 all other greenhouse gases whose values must be translated into CO_2 according to the parameters of international equivalence must be considered. In this case, while the

reduction of CO_2 for the same circulating fleet, can be obtained both by making delivery cycles more efficient and by using better vehicles from the point of view of environmental impact. It is precisely this last category that is clearly dependent on industrial production and the costs with which the most advanced production of vehicles goes on the market. The evolution of the automotive industrial sector strongly conditions the pursuit of the goals through city logistics.

Table 2. Conditioned impacts: targets and indicators related to city logistics (based on [19])

SDG	Goals and targets	Indicators
SDG 7 – Affordable and clean energy	7.2 By 2030, substantially increase the share of renewable energy in the global energy mix	7.2.1 Renewable energy share in the total final energy consumption
SDG 13 – Climate action	13.2 Integrate climate change measures into national policies, strategies and planning	13.2.2 Total greenhouse gas emissions per year
SDG 17 – Partnerships for the goals	17.18 By 2020, enhance capacity-building support to developing countries, including for least developed countries and small island developing States, to increase significantly the availability of high-quality, timely and reliable data disaggregated by income, gender, age, race, ethnicity, migratory status, disability, geographic location and other characteristics relevant in national contexts	17.18.1 Statistical capacity indicator for Sustainable Development Goal monitoring
	17.19 By 2030, build on existing initiatives to develop measurements of progress in sustainable development that complement the gross domestic product, and support the development of statistical capacity-building in developing countries	17.19.1 Dollar value of all resources made available to strengthen statistical capacity in developing countries
		17.19.2 Proportion of countries that (*a*) have conducted at least one population and housing census in the last 10 years; and (*b*) have achieved 100% birth registration and 80 per cent death registration

3.4 Indirect Impacts

Other SDGs are influenced by city logistics choices, but the TSM results are not directly usable to assess ex-ante modifications of indicators, but additional models are needed. Often the operational fact of using different models implies that the decisions taken, although belonging to the same local authority, derive from other technical sectors and not directly from the one that coordinates mobility policies.

In this context, the targets and indicators related to SDGs 4, 5, 8, 9, 10 can be considered (Table 3).

Table 3. Indirect impacts: targets and indicators related to city logistics (based on [19])

SDG	Goals and targets	Indicators
SDG 4 – Quality Education	4.4 By 2030, substantially increase the number of youth and adults who have relevant skills, including technical and vocational skills, for employment, decent jobs and entrepreneurship	4.4.1 Proportion of youth and adults with information and communication technology (ICT) skills, by type of skill
	4.7 By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship and appreciation of cultural diversity and of culture's contribution to sustainable development	4.7.1 Extent to which (i) global citizenship education and (ii) education for sustainable development are mainstreamed in (*a*) national education policies; (*b*) curricula; (*c*) teacher education; and (*d*) student assessment

(*continued*)

Table 3. (*continued*)

SDG	Goals and targets	Indicators
SDG 5 – Gender equality	5.1 End all forms of discrimination against all women and girls everywhere	5.1.1 Whether or not legal frameworks are in place to promote, enforce and monitor equality and non-discrimination on the basis of sex
	5.5 Ensure women's full and effective participation and equal opportunities for leadership at all levels of decision-making in political, economic and public life	5.5.1 Proportion of seats held by women in (a) national parliaments and (b) local governments
SDG 8 – Decent work and economic growth	8.1 Sustain per capita economic growth in accordance with national circumstances and, in particular, at least 7 per cent gross domestic product growth per annum in the least developed countries	8.1.1 Annual growth rate of real GDP per capita
	8.2 Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labor-intensive sectors	8.2.1 Annual growth rate of real GDP per employed person
SDG 9 – Industry, innovation and infrastructure	9.1 Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all	9.1.2 Passenger and freight volumes, by mode of transport

(*continued*)

Table 3. (*continued*)

SDG	Goals and targets	Indicators
	9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities	9.4.1 CO_2 emission per unit of value added
SDG -10 Reduced inequalities	10.1 By 2030, progressively achieve and sustain income growth of the bottom 40% of the population at a rate higher than the national average	10.1.1 Growth rates of household expenditure or income per capita among the bottom 40% of the population and the total population

SDG 4 is related to education. Specifically, targets 4.4 and 4.6 are to be considered. The first relates to the increase in ICT skills, and city logistics is developing better and better with the introduction of new generation ICT. The second is related to the growth of skills in sustainable development and city logistics is, as verified in this note, one of the most interesting fields for the study of development sustainability.

Furthermore, SDG 5, which refers to gender equality, should be considered given that it refers to ensuring the end of all forms of discrimination against women and girls and favoring their active participation in the city government and specifically in a sector that historically was dominated by the presence of men (targets 5.1.1 and 5.5.1).

SDG 8 must be considered in the two components relating to per capita growth per inhabitant and per capita growth per employee, both indicators that quantify the efficiency of the measures introduced and indicators that allow us to estimate at the territorial level the income increases due to the improvement of production and, therefore, to the employment multipliers.

SDG 9 is considered under two types of targets, the first (9.1) concerns the innovation capacity of logistics with the modification of the modal share, compared to other modalities; the second typology recalls what has already been said for target 11.6, namely the environmental impacts produced by new infrastructures.

SDG 10 is to be considered because it affects the reduction of inequalities even within the same country. Specifically, target 10.1 concerns the growth capacity of the areas lagging in development, which should be higher than that of the other areas of the country. City logistics with its contribution to innovation and integration with ICT and with the most advanced energy models can provide an important boost to growth.

4 Conclusions

The results presented in this paper can be condensed to highlight the limitations of current approaches to city logistics that consider only the efficiency of route costs. Based on this element, a bridge is identified between the general objectives of Agenda 2030 and the results of specific interventions in city logistics that can be evaluated ex ante with the TSM. This bridge makes it possible to identify measures that can directly affect the targets and indicators of Agenda2030 and measures that have an indirect impact. The results are important because the set of indicators has not been studied in the literature and Agenda 2030 is considered only as a generic reference framework.

With the proposed approach, the objectives of the Agenda 2030 cease to be mere declarations of principle and become real quantitative elements on which politicians, technicians of public administrations and private companies, researchers in both logistics and other competing subjects must work. All these professionals make it possible to work on measures that link Agenda 2030 to the daily realities of cities. Besides, the opportunity offered by telematics should be explored focusing on the transport-ICT interaction, as well as on the role of energy efficiency for meeting the goals of Agenda 2030. Therefore, it is thus possible to identify the further development roadmap. First, the role of city logistics in the framework of Agenda 20230 should be defined within the context of smart city with strong reference to the three pillars: energy in terms of production and use, transport and mobility, and information and communication technologies (ICT). Secondly, the development of a complete modelling formulation, which models the integration of the three pillars, needs to be promoted in order to be able to evaluate ex ante the actions and measures for the pursuit of the SDGs of Agenda 2030.

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Urban Air Mobility: Multi-objective Mixed Integer Programming Model for Solving the Drone Scheduling Problem

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Abstract. In this paper the drone scheduling problem was considered. The mixed integer linear programming mathematical formulation for the considered problem based on minimizing total delays in servicing tasks and total flying time of all drones is proposed. The model takes into account tasks duration and significance. The mathematical formulation has been tested on the hypothetical examples. The generated mixed integer linear programs have been solved by CPLEX. The obtained results show that task assignments on fleet of drones depend on drone speed and the number of drones analyzed.

Keywords: Drones · UAM · scheduling · mixed integer programming · urban airspace

1 Introduction

Cohen et al. [1], in their paper about history, ecosystem, market potential, and challenges of Urban Air Mobility (UAM) define it as an emerging concept which envisions a safe, efficient, accessible, sustainable, affordable, and quiet air transportation system for (among other services) – goods/cargo delivery within or traversing metropolitan areas.

During the last few years, interest in the potential use of Unmanned Aerial Vehicles (UAV) for the delivery of small parcels has arisen due to their competitive advantages. Drones benefit the delivery of small parcels because they are: i) not restricted to established road networks, ii) do not require pilots, iii) are low cost, iv) do not require launching infrastructures, and v) in disease outbreaks, they can reduce the physical interaction between victims and rescue teams. Given the unique abilities of drones, the delivery of time-sensitive medical items to rural and suburban areas via drones can save time, cost, and, above all, people's lives [2].

Persson [3] in its work identifies "emerging drivers for drones' application in last-mile delivery, barriers for drones' application in last-mile delivery, and approaches for implementing drones in last-mile delivery". He also stated that drone routing problem on last-mile delivery is one of the currently most researched topics. Goal of solving this problem is to find the optimal delivery path at a minimum cost given a set of locations.

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Drones are seen here as a tool for a last-mile delivery from a truck with whom is working in tandem.

Borghetti et al. [4] studied usability of drones for last-mile delivery in Milan, Italy. For that purpose they performed a stated preference survey among end-users to assess their propensity towards drones. Based on findings they designed a delivery service by drones. Study shows that new service can be successfully used for small and light package deliveries, reducing in such a way environmental and social impacts, while ensuring profits delivery provider.

Drones are receiving popularity with time due to their advanced mobility. Although they were initially deployed for military purposes, they now have a wide array of applications in various public and private sectors. Drone scheduling is associated with optimization of drone flight routes and may include other features, such as determination of arrival time at each node, utilization of drones, battery capacity considerations, and battery recharging considerations.

Torabbeigi et al. [5] were trying to find a parcel delivery schedule using drones considering the battery consumption rate as a function of payload, using a mixed integer linear programming problem (MILP). The "least number of drones and their flight paths to deliver parcels while ensuring the safe return of the drones with respect to the battery charge level" were obtained as results. Similarly Bruni et al. [6] have proposed a metaheuristic "combining variable neighborhood descent with a cut generation approach" to resolve routing problem considering battery consumption rates.

Pachayappan and Sudhakar [7] are determining optimal pickup and delivery routes in drone operations minimizing the distance traveled to complete the scheduled deliveries and ensuring the optimal use of the battery capacity and safe return. They proposed a Mixed-Integer Linear Programming (MILP) model.

Moadab et al. [8] were studying a last-mile delivery problem in which a set of drones are operated in coordination with public transportation system used to enable drones to charge their batteries. For that purpose they proposed mathematical model based on Vehicle routing Problem which objective function was aiming to minimize the total energy that drones consumed in delivery operations.

Pasha et al. [9] conducts an extensive survey of the scientific literature that assessed drone scheduling problem They grouped the collected studies into different categories, including general drone scheduling, drone scheduling for delivery of goods, drone scheduling for monitoring, and drone scheduling with recharge considerations.

Ghelichi et al. [2] presents an optimization model to design the logistics for a fleet of drones for timely delivery of medical packages to remote locations. They present a time-slot formulation to model a location-scheduling problem to determine a set of trips for the available fleet of drones such that the total completion time of all trips is minimized. The proposed model aims to i) find optimal locations of charging stations, ii) schedule and sequence deliveries, and iii) determine a set of trips for each drone. They implemented a case study for Louisville, KY to provide in-depth managerial insights into costs and system performance metrics.

Deng et al. [10] were studying the problem of serving multiple customers with one drone flight considering energy consumption. For that, they have developed a multi-UAV task allocation model combined with vehicle path planning model. They proposed

a hybrid heuristic algorithm based on an improved K-means algorithm and ant colony optimization.

Li et al. [11] have considered parcel delivery in low-altitude urban airspace and proposed UAV traffic management system which includes path planning, conflict detection and resolution and airspace resource allocation.

Having in mind importance of the drone scheduling problem in the scientific community, in this paper a multi-objective mixed integer programming model for drone scheduling problem was proposed. The model was used to find optimal schedules for all drones within considered urban area.

Paper is organized in a following way. After Introduction section which presents a literature survey, in following section some drone operation and urban airspace constraints are presented followed by drone flight routing assumptions. Section III contains statement of the problem while Section IV detailed mathematical formulation of the drone scheduling problem. Numerical example was presented in Section V followed with brief analysis of results and some findings. Section VI presents some conclusions and direction for further research.

2 Drone Operation Constraints and Routing Assumptions

Routing (determining of the trajectory) for multiple drones in urban environments, where obstacles of different heights exist, become an important problem in drone operations. This problem is even more challenging in case of Beyond Visual Line of Site (BVLOS) operations. The objective of route design is to find suitable trajectories in 3D environment while ensuring collision-free navigation. The collision is prevented by three possible alternatives: i) forcing the drone to statically hover, so its peer can pass first, ii) making it fly at a different altitude, or iii) completely changing its path.

Multiple charging stations are made available to allow the drones to recharge their batteries when needed [12]. The proposed collision-free navigation solutions are proactive approaches determining the trip plan of each member of the fleet beforehand, i.e., before the motion of the fleet to ensure a safe flight for the drones [12]. Path (trajectory) planning (routing) is one of the fundamental problems that have to be solved.

2.1 Drone Operation Constrains

The following operation constraints are assumed in this study:

- Climb and descend are limited with 20 degrees off the horizon. For the purpose of calculation safe value of 15 degrees was used. With speed of 20m/s and angle of 15 degrees climb/descend speed of about 5.2 m/s is obtained.
- Drone in use is designed to keep constant air speed of 20m/s. Depending on the wind ground speed vary between 15–25 m/s (depending whether it is head or tail wind).
- Drone trajectory auto correction is conducted by two options
  - o drone is always trying to get to the next point, it means that if it's blown off the track it will maintain straight line to the next point,

p drone is following the line, then, if it's blown off the track, it will get on track back and then continue flight.

- Drone is not equipped with any visual obstacle avoidance system.
- Drone is keeping track in terms of height with deviation less than 10 m.
- Drone landing takes at least one minute.

2.2 Urban Airspace Constraints

The very low altitude urban airspace, where drones are expected to operate, contains operational complexities, due to the presence of obstacles as well as temporary and permanent no-fly-zones. This part of the airspace is also frequently occupied by general aviation aircraft and helicopters. Therefore, the urban airspace is heavily constrained. Nevertheless, many of these operational complexities (and their characteristics) are shared by ground-based traffic, for which there exists a wide body of literature [13].

Similar to road vehicles, drones can employ existing street networks and, thus, 'flyover-streets' in constrained urban spaces. However, with the expected large-scale drone traffic volumes, simply flying over streets may not be adequate to ensure airspace safety. When drones fly in competing travel directions in a constrained environment, a large number of conflicts would be triggered, due to high average relative velocities and limited flexibility of the airspace.

As a result, applying segmentation and alignment principles to this portion of the airspace, in particular, would organize traffic into different altitude layers with respect to travel directions and, thus, add more structure to the constrained environment [13].

2.3 Drone Flight Routing Assumptions

Considering urban airspace and drone operation constrains mentioned above, it was possible to define flight path that would be convenient for usage in this study. For illustration purposes a virtual city was used. In order to simplify solution as much as possible, it was assumed that data about city topography and obstacle heights, as well as geo location of city stations are known, e.g. three stations with corresponding coordinates (Station1: lat1, lon1; Station2: lat2, lon2; Station3: lat3, lon3 (Fig. 1)).

Figure 2 represents drone vertical flight path illustration at Virtual City. Station 1 is defined by latitude, longitude, elevation and object height. Station 2 is defined the same way. *Pt* is take-off point with same parameters as Station 1. *Pl* is landing point with same parameters as Station 2. *Pc* is defined by latitude, longitude and elevation and represents point where take-off and climb is finished and drone flight is transformed to cruise at certain height. *Pd* is point defined by latitude, longitude and elevation (same elevation as *Pc*) where descent for landing begins.

If *No flight area* is activated for the time drone has to fly from Station2 to Station3 (or vice versa), flight path is set to alternative path that avoids prohibited area (as shown on Fig. 3). Point *Pas* (Fig. 3) is starting point of alternative route. When drone reaches cruising height, it reroutes from direct route to alternative. *Pae* is point where alternative route ends and drone is pointed to destination.

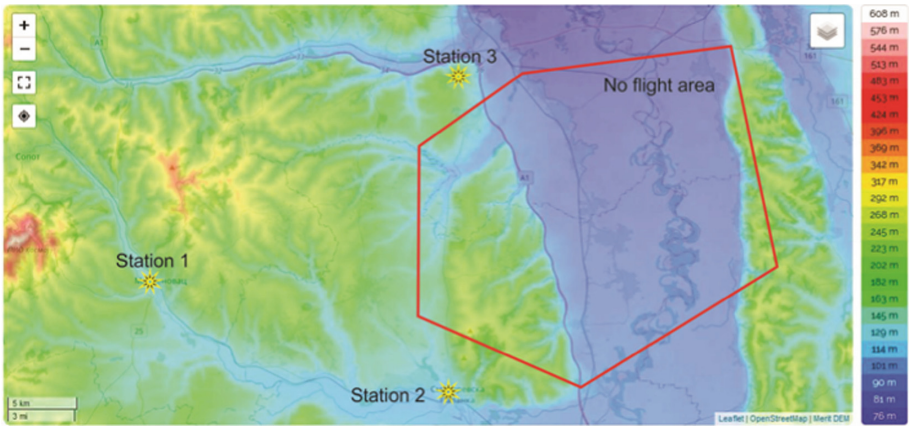

Fig. 1. Virtual city stations with corresponding geo location and elevation. Predefined No flight area is also represented.

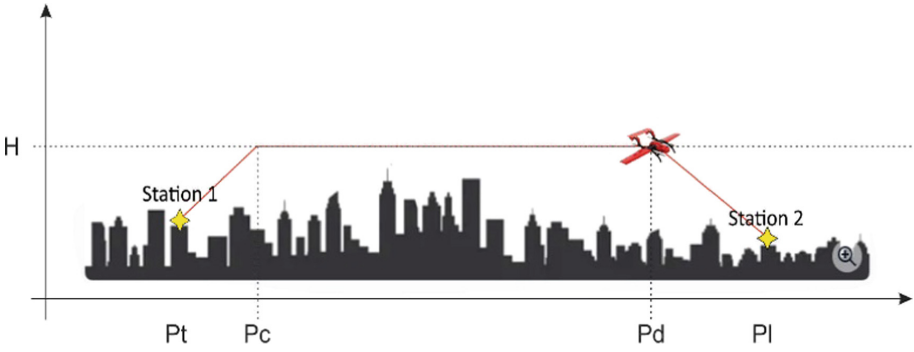

Fig. 2. Drone vertical flight profile illustration

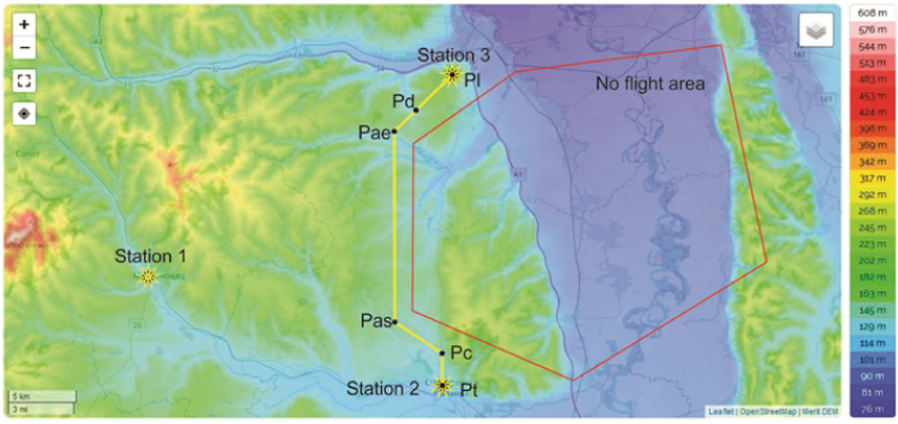

Fig. 3. Drone flight path Virtual City illustration with No flight area activated

3 Statement of the Problem

The problem of the assignment of the tasks to the available drones was considered in this study. It was supposed that there are n tasks, m drones and d drone stations. At the beginning, all drones are located at the same depot. Each task has the following characteristics: origin station (i, $i = 1,\ldots, d$), destination station ($j, j = 1,\ldots, d$), loading time at the station i and unloading time at the station j, the time when the service of the task should start and the coefficient that represents the significance of the task.

In the considered problem each task should be served by one drone. When the drone serves the last assigned task it has to return at the depot. All drones have the same characteristics.

The most important goal in this problem is to find the schedules of drones in the way to minimize the deviation from the required beginning of service of the tasks. The significance of the tasks should be also taken into consideration. The second goal is to minimize the drones' activities (for example, the total flying time of all drones).

Following modeling assumptions are used: each drone can carry only one parcel which payload is constant, battery consumption rate is not taken into account, delivery between fixed stations (e.g. hospitals) are considered (not last-mile delivery from trucks e.g.), operations are BVLOS, urban network contain finite number of fixed stations.

4 Mathematical Formulation for the Drone Scheduling Problem

The depot was denoted as node 0 and the tasks as nodes from 1 to n. Let explain in more detail how the task was represented as the node. Suppose that the drone, located at the depot, must serve two tasks and return to the depot. In the first task, the drone flies from station 1 to station 2, and in the second task, the drone flies from station 3 to station 4 (Fig. 4). It could be noticed that the drone will fly in the following way: depot – station 1 – station 2 – station 3 – station 4 – depot. This example can be also represented in the following way: the depot is node 0, the first task is node 1, and the second task is node 2. Now, the drone has the following route: 0 – 1 – 2 – 0 (Fig. 5). Comparing these two paths, one can notice that the travel time between nodes 0 and 1 is the same as the travel time between the depot and the origin station of task 1.

The travel time between nodes 1 and 2 is the travel time between the destination station of task 1 and the origin station of task 2.

A multi-objective mixed integer programming mathematical formulation for the considered problem was developed. The notations used in this formulation are given bellow.

Input data:

t_{ij} – travel time from the destination node of the task i to origin node of the task j,

tl_i – loading time of task i,

ts_i – service time of task i (travel time between the origin to destination station of task i),

tu_i – unloading time of task i,

r_j – time when the service of task j should start,

M – large positive number,

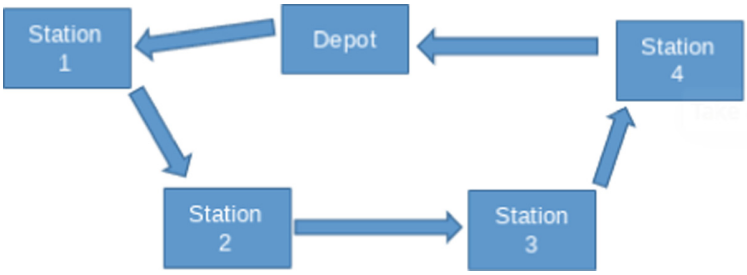

Fig. 4. The example of the drone route

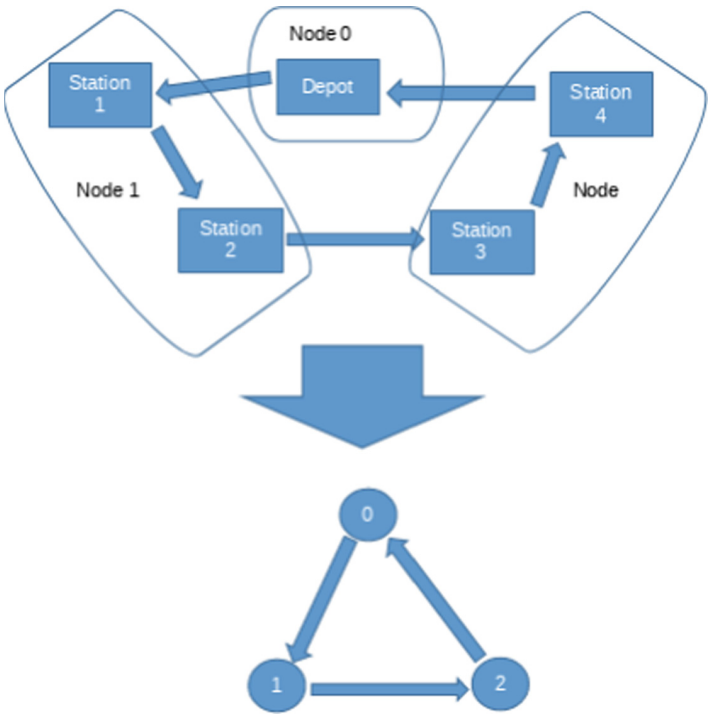

Fig. 5. The drone path when the depot and the tasks are given as the nodes

w_j – the coefficient of significance of the task j,
Decision variables:

$$x_{ijk} = \begin{cases} 1, & \textit{if the drone } k \textit{ after task } i \textit{ is going to serve task } j \\ 0, & \textit{otherwise} \end{cases}$$

s_{jk} – the time when the drone k starts to service of the task j,

y_{jk} – decision variable that represent delay from the required start of servicing of the task j by the drone k

The mixed integer programming model was developed to assign the tasks to the available drones. This mathematical formulation can be given in the following way:

$$\begin{aligned} &\text{Minimize} \\ &F_1 = \sum_{j=1}^{n} \sum_{k=1}^{m} w_j y_{jk} \end{aligned} \tag{1}$$

$$\begin{aligned} &\text{Minimize} \\ &F_2 = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ i \neq j}}^{n} \sum_{k=1}^{m} t_{ij} x_{ijk} \end{aligned} \tag{2}$$

Subject to:

$$\sum_{\substack{i=0 \\ i \neq j}}^{n} \sum_{k=1}^{m} x_{ijk} = 1 \quad \forall j = 1, \cdots, n \tag{3}$$

$$\sum_{\substack{i=0 \\ i \neq j}}^{n} x_{ijk} - \sum_{\substack{i=0 \\ i \neq j}}^{n} x_{jik} = 0 \quad \forall j = 1, \cdots, n; k = 1, \cdots, m \tag{4}$$

$$\sum_{j=1}^{n} x_{0jk} \leq 1 \quad \forall k = 1, \cdots, m \tag{5}$$

$$\sum_{i=1}^{n} x_{i0k} \leq 1 \quad \forall k = 1, \cdots, m \tag{6}$$

$$s_{ik} + tl_i + ts_i + tu_i + t_{ij} - M \cdot \left(1 - x_{ijk}\right) \leq s_{jk} \quad \forall i = 1, \cdots, n; j = 1, \cdots, n;\ i \neq j;\ k = 1, \cdots, m \tag{7}$$

$$s_{jk} - y_{jk} = r_j \quad \forall j = 1, \cdots, n; k = 1, \cdots, m \tag{8}$$

$$x_{ijk} = \{0, 1\} \quad \forall i = 1, \cdots, n; j = 1, \cdots, n; i \neq j; k = 1, \cdots, m \tag{9}$$

$$s_{jk} \geq 0 \quad \forall j = 1, \cdots, n; k = 1, \cdots, m \tag{10}$$

$$y_{jk} \geq 0 \quad \forall j = 1, \cdots, n; k = 1, \cdots, m \tag{11}$$

Objective function (1) represents the total delay in servicing tasks. Objective function (2) calculates the total flying time of all drones. The both objective functions should be minimized.

Constraint (3) guarantees that all tasks will be served. Constraint (4) enables that the drone after finishing one task will go to another one or it will return to the depot. Constraint (5) defines that the drone can go from the depot to just one task. In the similar way constraint (6) guaranty that the drone have to return to the depot after finishing last assigned task. The time when the drone k will start to service the task j calculates according to the constraint (7). Delay of servicing of the tasks calculates by the constraint (8). Constraints (9), (10) and (11) define decision variables.

5 Numerical Example

In many cases of the considered problem the first objective function is significantly more important than the second one. Because of that, in this research, a lexicographic method of multi-objective optimizations has been applied.

According to this method, two mixed-integer programs have to be solved. In the first one, the first objective function and the set of constraints (3 - 11) have to be used.

After solving this program, the solution and the best value for the first objective function (let denote this value of the objective function with F_1^*) was obtained. The second mixed integer program consists of the second objective functions, the set of constraints (3–11), and one new constraint: $F_1 \leq F_1^*$. In that way, the solution was optimized in the way to minimize the second objective function, while the first objective function will not be worsened.

The lexicographic method has been applied to a small hypothetical example with five stations and ten tasks. For the stations the locations of the hospitals in the city of Belgrade (Republic of Serbia) are chosen. It was assumed that the depot is at the same location as the first station. Eight scenarios were analyzed depending on the speed of drones, the number of drones, and the tasks significance coefficients:

- Scenario 1: 3 drones with the average speed of 50 km/h for traveling and 10 m/s for taking off and landing and the same significance coefficients of the tasks,
- Scenario 2: 3 drones with the average speed of 50 km/h for traveling and 10 m/s for taking off and landing and different significance coefficients of the tasks,
- Scenario 3: 5 drones with the average speed of 50 km/h for traveling and 10 m/s for taking off and landing and the same significance coefficients of the tasks,
- Scenario 4: 5 drones with the average speed of 50 km/h for traveling and 10 m/s for taking off and landing and the different significance coefficients of the tasks,
- Scenario 5: 3 drones with the average speed of 30 km/h for traveling and 5 m/s for taking off and landing and the same significance coefficients of the tasks,
- Scenario 6: 3 drones with the average speed of 30 km/h for traveling and 5 m/s for taking off and landing and the different significance coefficients of the tasks,
- Scenario 7: 5 drones with the average speed of 30 km/h for traveling and 5 m/s for taking off and landing and the same significance coefficients of the tasks,
- Scenario 8: 5 drones with the average speed of 30 km/h for traveling and 5 m/s for taking off and landing and the different significance coefficients of the tasks.

Also, it was supposed that drones fly at the height of 100 m (Fig. 2). The total travel time (taking off time + travel time + landing time) in minutes between the stations for the first four scenarios are given in Table 1, and for the rest of them are given in Table 2. The characteristics of the tasks are given in Table 3 (duration) and Table 4 (significance).

All test examples were solved with CPLEX 20.1 software. The computer with the following performances was used: AMD Ryzen 7 3800 X with 32 GB of RAM memory, operating system: Ubuntu 21.10.

Table 1. The total travel time between the drone ports for the scenarios from 1 to 4

	Depot	St. 1	St. 2	St. 3	St. 4	St. 5
Depot	0	0	4.54	2.67	5.29	8.41
St. 1	0	0	4.54	2.67	5.29	8.41
St. 2	4.54	4.54	0	2.25	6.11	12.15
St. 3	2.67	2.67	2.25	0	5.66	10.28
St. 4	5.29	5.29	6.11	5.66	0	12.47
St. 5	8.41	8.41	12.15	10.28	12.47	0

Table 2. The total travel time between the drone ports for the scenarios from 5 and 8

	Depot	St. 1	St. 2	St. 3	St. 4	St. 5
Depot	0	0	7.68	4.56	8.93	14.13
St. 1	0	0	7.68	4.56	8.93	14.13
St. 2	7.68	7.68	0	3.87	10.29	20.35
St. 3	4.56	4.56	3.87	0	9.54	17.24
St. 4	8.93	8.93	10.29	9.54	0	20.90
St. 5	14.13	14.13	20.35	17.24	20.90	0

Table 3. The characteristics of the tasks – Duration

Task	Origin station	Destination station	Loading time [min]	Unloading time [min]
1	1	2	1	1
2	3	5	1	1
3	4	3	1	1
4	2	4	1	1
5	5	1	1	1
6	4	2	1	1
7	1	5	1	1
8	2	3	1	1
9	3	1	1	1
10	3	4	1	1

Table 4. The characteristics of the tasks - Significance

Task	Start of the service [min]	Significance	
		scenarios: 1, 3, 5, 7	scenarios: 2, 4, 6, 8
1	5	1	1
2	10	1	1.25
3	15	1	1.5
4	20	1	1.75
5	20	1	2
6	25	1	2.25
7	25	1	2.5
8	25	1	2.75
9	30	1	3
10	30	1	3.25

For each scenario, two mixed integer programs were solved, and the obtained results are given in Tables 5 and 6. Table 5 shows the obtained routes for each drone, and Table 6 shows the values of the objective functions as well as the required CPU times. The values for F_1, given in column 2 in Table 6, and the CPU time given in column 4 in Table 6, were obtained by solving the first mixed integer programs. The values for F_2 and the CPU times in column 5 in Table 6 were obtained by solving the second mixed integer programs.

It can be noticed that speed and the number of drones significantly influenced the quality of solutions. Comparing scenarios 1 and 3, 2 and 4, 5 and 7, 6 and 8, it can be seen that in all of these cases the solutions with a higher number of drones are significantly better. Similarly, comparing scenarios 1 and 5, 2 and 6, 3 and 7, 4 and 8, it can be concluded that faster drones significantly outperform the slower ones. Also, it can be noticed that the different significance of tasks mainly did not make a big difference between the routes.

It is very interesting to take into consideration the CPU time for solving considered examples. Generally, this is a small example and because of that, the CPU times are very small for all scenarios. Comparing the CPU times for solving mixed integer programs for three and five drones it can be concluded that examples with more drones can be solved faster. Also, the interesting fact is that solving the second mixed integer program (the second model) needs less time than the first one.

Table 5. The obtained solutions

Scenario	Drone	Route (assigned tasks)
1	1	0 - 2 - 5 - 10 - 0
	2	0 - 3 - 8 - 9 - 7 - 0
	3	0 - 1 - 4 - 6 - 0
2	1	0 - 1 - 4 - 6 - 0
	2	0 - 3 - 8 - 9 - 7 - 0
	3	0 - 2 - 5 - 10 - 0
3	1	0 - 1 - 8 - 10 - 0
	2	0 - 4 - 6 - 0
	3	0 - 2 - 5 - 0
	4	0 - 7 - 0
	5	0 - 3 - 9 - 0
4	1	0 - 1 - 4 - 6 - 0
	2	0 - 8 - 10 - 0
	3	0 - 7 - 0
	4	0 - 2 - 5 - 0
	5	0 - 3 - 9 - 0
5	1	0 - 1 - 4 - 6 - 10 - 0
	2	0 - 2 - 5 - 0
	3	0 - 3 - 8 - 9 - 7 - 0
6	1	0 - 1 - 8 - 9 - 7 - 0
	2	0 - 2 - 5 - 0
	3	0 - 3 - 10 - 6 - 0
7	1	0 - 1 - 8 - 9 - 0
	2	0 - 2 - 5 - 0
	3	0 - 7 - 0
	4	0 - 4 - 6 - 0
	5	0 - 3 - 10 - 0
8	1	0 - 8 - 9 - 0
	2	0 - 2 - 5 - 0
	3	0 - 3 - 10 - 0
	4	0 - 7 - 0
	5	0 - 1 - 4 - 6 - 0

Table 6. The solution characteristics

Scenario	Objective functions		CPU time [sec]	
	F_1	F_2	first model	second model
1	20.42	31.12	0.65	0.13
2	53.15	31.12	1.04	0.19
3	5.39	30.74	0.18	0.04
4	11.56	30.74	0.2	0.02
5	64.51	44.29	2.96	0.25
6	147.22	51.91	5.74	0.79
7	17.4	51.91	0.27	0.15
8	37.49	51.91	0.22	0.1

6 Conclusions

Proposed multi-objective mixed integer programming model for drone scheduling problem solved by CPLEX have provided in fast manner a route (assigned tasks) per each drone.

The obtained results show that task assignments on fleet of drones depend on drone speed and the number of drones analyzed.

Future research are planned to go in two directions. One is relaxation of certain assumptions, such as e.g. inclusion of battery consumption in a criteria or use of different payload parcels, increase of network of stations and integration of model into digital map of the city.

Other research direction is related to testing examples with more stations and tasks. Most probably, the solution approach proposed in this report will cause much bigger values of the CPU time. In that case, it should be developed some heuristic or metaheuristic algorithms for the considered problem.

Limitation for selection of optimal drone route in this study is that drones do not have any sensors (cameras, radar, lidar, etc.) that can influence route optimization.

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Urban Slum Upgrading: A Model for Expeditious Estimation of the Cost of Interventions

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Abstract. More than a billion people around the world live in slums in undignified and precarious living conditions. These are places of high poverty characterized by overcrowding, poor housing facilities and inadequate access to basic services such as clean water, electricity and sanitation. Slums today testify to the two main challenges to human settlement development in this millennium: rapid urbanization and the urbanization of poverty. Slums, in fact, are the increasingly common solution of providing housing for low income-to people. Therefore, the phenomenon of slums is an important contemporary challenge that requires well-structured intervention programs aimed at poverty reduction and urban transformation. In light of the above and in line with the goals mentioned in both the Sustainable Development Goals (SDGs) and the New Urban Agenda (NUA), urban slum redevelopment interventions would make it possible to improve the quality of existing settlements, and reverse their decline, by transforming and making the spaces better, safer and more sustainable places where everyone can live and work. In this sense, the purpose of the work is to define possible intervention scenarios and characterize a model for the expeditious estimation of related construction costs. The model, which is based on a synthetic-comparative procedure, makes it possible to provide an economic reference that is useful in determining the amount of resources to be allocated for the urban upgrading of slums, a symbol of profound social inequality.

Keywords: Slum · Appraisal Issues · Cost-Approach

1 Introduction

According to the *World Cities Report* [1], there are about 1.6 billion people living in inadequate housing, nearly 20 percent of the world's population. Of these, 1 billion reside in slums and informal settlements. In the next 30 years, in the absence of appropriate intervention measures, this number could even double. Indeed, current urbanization trends indicate that an additional three billion people will live in cities by 2050, increasing the urban share of the world's population to two-thirds [2].

The challenge of housing and slums, therefore, remains a critical factor in the persistence of poverty in the world: millions of urban residents are continually deprived of

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their right to an adequate standard of living and housing. In such a scenario, the 2030 Agenda's goal of eradicating poverty in all its forms looks a long way off.

Rapid population growth, mass migration from rural to urban areas, and the inability of the market and government to meet the huge demand for decent and affordable housing are the main factors contributing to the development of slums [3]. In addition, there are poor government investments in infrastructure, ineffective urban planning systems and misguided regulatory systems that still do not consider slum neighborhoods as an integral part of cities [4, 5].

Slums are, therefore, the most manifest expression of poverty and social and economic inequality on the Planet, and although spread globally, most of them are located in the large urban areas of Southeast Asia, sub-Saharan Africa and South America [6].

Often covering very large areas equal to entire towns or villages, however, slums are not recognized by the state and their informal existence almost always results in the absence of minimum essential services, such as water and sanitation, and adequate security measures.

They are overcrowded, unsanitary, illegally built urban spaces with unsuitable materials, located in areas exposed to environmental hazards and lacking public spaces and services. For low-income people, however, slums are still the only means of providing an answer, albeit partial, to their needs.

The slum phenomenon is, therefore, one of the main contemporary challenges facing the world and requires well-structured intervention programs, whose economic aspect is currently still poorly investigated.

In this sense, the work is aimed at characterizing a model for expeditious estimation of the construction costs of possible intervention scenarios aimed at the redevelopment of slums; this is with the purpose of providing an economic reference useful for estimating the amount of resources to be allocated.

The study is structured as follows. Paragraph 2 defines the slum phenomenon and its specific characteristics. Paragraph 3 outlines the different policy and intervention approaches adopted over the years to address the slum issue. Paragraph 4 characterizes a model for expeditious estimation of intervention costs for slum upgrading; this model is made explicit for different intervention scenarios. The paper concludes with reflections on the limitations and potential of the proposed estimation approach.

2 Definition and Characteristics of a Slum

The term "slum" was first used in 1812 by J.H Vaux as a synonym for "racket" or "criminal traffic," indicating, rather than a place, a deprived social condition [7, 8]. It was in the late 19th century that the term began to have a spatial connotation. In 1895, in *The Slum of the Great Cities*, the word "slum" becomes a metaphor for the degradation, moral and civil, of "an area of dirty back streets inhabited by a sordid and criminal population" [9, 10].

In 2002, at the UN conference in Nairobi, the definition of a slum was officially adopted as a densely populated emerged informally, characterized by dilapidated buildings and living conditions below minimum survival standards [11].

Furthermore, according to UN-Habitat (2003), a slum household is defined as a group of individuals living under one roof in an urban area who lack one or more of the following:

1. access to water, i.e., access to a sufficient amount of potable water for family use and at an affordable price;
2. access to sanitation, meaning access to a private bathroom or a public bathroom shared with a reasonable number of people;
3. sufficient living space, implying the presence of less than three people per room of a minimum of 4 square meters;
4. quality/duration of housing, i.e., the presence of adequate and permanent structures built in non-hazardous locations;
5. guarantees of possession conditional on the existence of documentation proving possession status or the existence of protection against possible eviction.

In light of the physical and legal characteristics dictated by the UN-Habitat, in fact, one of the main problems of slums around the world is the absence of essential services: we refer to sanitation facilities and sources of drinking water, as well as effective waste collection systems, electricity supply, rainwater drainage, etc. This results in unhealthy living conditions that, combined with malnutrition, feed the spread of diseases such as malaria, tuberculosis, etc.

Moreover, most of the houses are overcrowded, occupied by five or more people, from the same or different families, sharing a single apartment or even a single room intended for all functions. The latter is almost always built with substandard materials unsuitable for housing, given the local climatic and location conditions. Slum houses are, in fact, mostly made of sheet metal, sacks, wood, mud and reed walls and are located in dangerous areas or land unsuitable for settlement, as they are at risk of flooding or landslides, or near industrial plants and railway lines [12, 13].

Slum inhabitants also live in precarious conditions, in squatted housing since they lack a formal document to protect them against arbitrary illegal eviction by the state, harassment and any other threats. Often, in the absence of a legal address, people do not even have the ability to access social services such as subsidized health care or education.

These factors of social destabilization are often combined with the risk of high levels of crime: high poverty rates induce violence, abuse and underworld crime.

Economic subsistence also lacks, in most cases, a formal framework and any form of security [14]: the so-called *informal economy*, consisting of generally small-scale industries and businesses, is often the source of survival for the majority of the inhabitants and compensates for much of the formal sector's inability to provide goods and services [15–17]. In the informal sector, in fact, activities persist and even grow faster than large-scale enterprises in the formal sector. Informal jobs, however, are unskilled, pay very little, and provide no guarantees; in fact, they generate a subsistence economy that allows residents to survive but not to advance far enough to improve their living conditions.

3 Urban Redevelopment of Slums

In response to the sensitive and complex issue of slums, different policy approaches have been attempted in recent decades, evolving over time and in relation to the uniqueness of the needs to be met. This evolution was well outlined in *The Challenge of Slums* (2003), a global report by UN-Habitat [11].

As highlighted in the report, the 1970s were characterized by a general attitude of denial of the reality of slums and the rights of their communities. This induced an approach of "negligence" toward these settlements that were considered an inevitable but temporary problem to be addressed simply by aiming for greater economic development, both of urban and rural areas.

This solution proved to be unsuccessful and prompted more "repressive" policies that dealt with the problem by demolishing entire slums and evicting the inhabitants in mass, often without offering viable alternative solutions and without any compensation payments. This approach did not solve the problem of slums, which, in practice, were simply located toward the outskirts of cities, where access to land was easier and planning control was inexistent [18, 19].

In the late 1970s, slums were recognized as an enduring structural phenomenon, thus to be addressed by appropriate interventions recognized in a new approach of "Self-help and in situ upgrading." In the light of a new awareness of the right to housing and the protection of citizens against forced evictions, there are three main lines of action: (i) the provision of basic urban services; (ii) securing housing possession and implementing innovative land access practices; and (iii) innovative access to credit, adapted to the economic profile, needs and requirements of slum residents and communities [20].

The in situ redevelopment approach saw further evolution during the late 1980s–1990s, in which greater emphasis was placed on community involvement in decision-making, design and implementation of the regeneration of their own settlements; this allows for the implementation of interventions and transformations that are more appropriate and close to the cultural needs of citizens [21].

The scope of redevelopment, however, can vary from small-scale sectoral projects, such as street resurfacing or street lighting, to comprehensive housing and infrastructure projects, to integrated projects that combine building and environmental interventions with social and political empowerment programs [22–24].

Urban slum upgrading is in line with the current *Sustainable Development Goals* (SDG) Goal 11 – Sustainable Cities and Communities – which aims to make cities and human settlements inclusive, safe, resilient and sustainable. In detail, it also aims to redevelop slums by ensuring access to adequate, safe and affordable housing and basic services for all.

Also the *New Urban Agenda* (NUA), whose goals are closely related to those of the 2030 Agenda, promotes the improvement of living conditions for all against the persistence of multiple forms of poverty, inequality and environmental degradation, the main obstacles to sustainable development worldwide.

In recent years, many agencies, local governments, and Non-Governmental Organizations (NGO) have been involved in major slum upgrades in all regions of the world.

Examples of participatory slum redevelopment programs include the Empower Shack, an interdisciplinary housing development project directed by the Urban Think Tank (ETHZ) and the NGO Ikhayalami, in collaboration with the BT-Section community and local and international partners. The goal of the project is the redevelopment of informal settlements through an innovative and inclusive methodology based on four key components: (i) a prototype of two-level, innovative, affordable and sustainable housing; (ii) a participatory land-use planning process; (iii) integrated urban systems; and (iv) economic solutions to support the local community. The first intervention was implemented on the outskirts of Cape Town, South Africa, in the Khayelitsha district, a 4 km2 area where 400,000 people live. In 2015, the pilot project saw the construction of the first four houses, which were accompanied by new houses of different prototypes as well in the following years. Occupying a smaller portion than usual, the houses are developed on two levels, with basic local materials and relatively simple construction techniques: the supporting structure is made of wood and is covered with sheet metal, also designed to be self-built. In fact, community members had access to a microcredit system and were fully involved in the project as the driving force behind the reconstruction of their own homes with materials familiar to them.

Another good example of redevelopment is Slum Networking, an innovative approach to urban development in India. The brainchild of engineer Himanshu Parikh, the holistic approach has won numerous awards, including the Dubai Award the World Habitat Award 1994 and the Aga Khan Award for Architecture [25].

Slum Networking was first pioneered in 1997 in Indore, India, and is now being applied elsewhere. It mainly involves interventions to upgrade the sanitation system of an entire city using the network of slum settlements as a starting point.

In Indore, engineer Parikh implemented interventions aimed at connecting individual houses to the water and sewerage network, establishing a public lighting system, and resurfacing roads and common areas. These interventions, however, were designed as part of a broader strategy that included the "networking" of multiple slums, which in turn were connected to the already stable and functioning cities [26, 27]; this allowed for an overall improvement of the entire infrastructure network that was no longer weakened by the presence of discontinuity areas not served by infrastructure [28]. All of this has been achieved at a fraction of the cost of conventional approaches. Although not a housing program, the improved infrastructure results in a significant increase in the quality of housing and health standards in the slum. The intervention in Indore, moreover, was the result of intensive collaboration, including financial, of local government agencies, private companies, NGOs and local residents. According to Parikh, in fact, the approach can only work with the cooperation and active participation of slum residents: their direct involvement increases the willingness on the part of the community to care for and support what has been achieved, thus avoiding the lack of assistance that has proven in the past to be one of the main obstacles to slum improvement programs [27, 29].

4 Model for Expeditious Estimation of Intervention Costs

Today, one of the main issues negatively affecting the improvement of living conditions in slum communities is the lack of real political will to address this complex problem in a structured, sustainable and large-scale way [30].

In fact, with the increased demand for health, education, transportation and all other kinds of services, administrations fail to secure appropriate solutions. The lack of resources has contributed to the imbalances between cities as most investments are made only in the capital. For this reason, in smaller cities, the projects implemented are almost always possible thanks to foreign funding, particularly from NGOs. The latter, however, contribute to the deresponsibility of the national government by going to act where the state is absent by verifying, in addition, its proper use of international assistance money, which is often wrongly used.

The economic aspect related to slum upgrading interventions is still little investigated. In light of the poverty, environmental degradation, and unhealthy conditions in which slum communities live, only a few useful interventions would suffice to meet the minimum requirements set by UN-Habitat (Paragraph 2) to ensure at least decent living conditions for citizens.

However, it is clear that urban redevelopment interventions alone cannot improve the overall quality of life of slum residents unless their economic and social conditions also change. For slum inhabitants to improve their standard of living, it is necessary to provide them with opportunities to be able to increase their incomes [31].

Three possible reference scenarios are presented.

a) **Minimum level of intervention**, which is the implementation of actions such that meet the minimum requirements set by UN-Habitat (Paragraph 2). The reference is to the implementation of actions that ensure:

   – a good level of structural quality and sufficient living space;
   – access to drinking water through the implementation of water distribution and collection systems;
   – access to improved sanitation through the construction of a sewerage system.

b) **Barely satisfactory level of intervention,** which includes upgrading works aimed at improving the level of livability of the slum. In detail, the interventions included in the minimum level are added to those required for the:

   – remediation of polluted areas;
   – waste management;
   – implementation of road networks;
   – implementation of drainage networks;
   – implementation of green infrastructure.

c) **Fully satisfactory level of intervention** which involves socio-economic improvements aimed at generating employment and business activities in light of the severe poverty and lack of income that characterize the slums. Useful initiatives could include: the creation of workshops for the development of professional and entrepreneurial skills; advice to aspiring entrepreneurs on registering, setting up and managing their businesses; technical education scholarships to promising students;

the activation of funds to secure interest-free loans for raw materials, machinery and institution [32].

In order to provide an economic reference useful for determining the amount of resources to be allocated for urban slum upgrading interventions, having identified possible intervention scenarios, it is possible to structure a model for the expeditious estimation of the related construction costs [33–35]. This cost estimate comes in useful, even in the absence of a final design, for feasibility assessments of a project and for budget decisions.

The cost approach is a methodology recognized by international standards and the scientific bibliography of Estimate. It involves determining the economic value that would be placed on the building today if it were destroyed or needed to be completely replaced [36, 37].

Construction Cost CC is sum of Construction Technical Cost CTC, General Expenses SG and Constructor's Technical Profit UTC:

$$CC = TCC + GC + CTP \tag{1}$$

$$TCC = MT + L + FT \tag{2}$$

In detail, the TCC item represents the technical cost of construction whose rate is composed of the direct variable costs that depend in a directly proportional form on the work to be performed: these are the costs related to materials (MT), labor (L) and freight and transportation (FT). This technical cost TCC greatly affects the overall construction cost since it is to it that the other cost items are linked.

GC expresses the general costs composed of indirect, variable, and fixed costs. In detail, the variable indirect costs do not depend on the work produced but simply on the opening of the construction site (costs concerning the setting up of the construction site itself, personnel, safety costs). Fixed costs, instead, are the general site costs that are independent of site activity (personnel employed, financial charges, etc.).

CTP represents Constructor's Technical Profit, i.e., remuneration for the organization of construction production and work phases, in addition to any risks associated with increased input costs, sanctions for delays or problems in the work.

In line with the previously outlined intervention scenarios, formulation (1) and formulation (2) can be made explicit as follows:

$$CC_{(a)} = TCC_{(a)} + GC + CTP \tag{3}$$

$$TCC_{(a)} = (TC_d + TCC_h) \times S_h + (TCC_w + TCC_{ww}) \times L_s \tag{4}$$

$$CC_{(b)} = TC_{(b)} + GC + CTP \tag{5}$$

$$TCC_{(b)} = TCC_{(a)} + TCC_g \times S_h + TCC_{dr} \times L_s + TCC_s \times S_s \tag{6}$$

Respectively for the minimum level (a) and the barely satisfactory level (b), each cost item represents:

- TC_d – Technical cost of demolition, usually expressed per square meter or cubic meter;

- TCC_h – Technical cost of housing construction, per square meter
- TCC_w – Technical cost of water network construction, expressed in linear meters;
- TCC_{ww} – Technical cost of construction of wastewater collection network, in linear meters;
- TCC_g – Technical cost of green infrastructure construction expressed in square meters;
- TCC_{dr} – Technical cost of drainage network, in linear meters;
- TCC_s – Technical cost of construction of road networks measured in square meters.

The cost items are multiplied by: the surface area to be allocated to housing (S_h); the surface area to be allocated to road networks (S_s); and the surface area to be allocated to water, drainage and wastewater collection networks (L_s).

Regarding the fully satisfactory level (c), no particular construction works are planned, rather actions to improve the socio-economic network of the slums. For this reason, there is no explicit formula concerning construction costs.

For the purpose of estimating the construction cost, in light of the information needs, processing time and the degree of reliability required by the forecast, two procedures can be used: (i) analytical; (ii) synthetic-comparative.

The analytical procedure (i) focuses on the analysis of the production process of construction and, therefore, on the identification and quantification of all the production factors involved in it. This procedure, therefore, provides for the preparation of an estimated metric calculation that guarantees an accurate amount of the resources needed to carry out an intervention but, at the same time, requires the preparation of a final or executive project to which reference must be made. It is easy to deduce the difficulty that would be encountered in applying the analytical procedure to a large area such as slums, where a metric calculation would have to be processed for each civil work to be carried out.

Definitely more expeditious, and suitable for preliminary cost estimation of slum upgrading interventions, is the synthetic-comparative procedure (ii). The latter estimates construction costs through comparison with known costs of similar works already carried out. The procedure involves:

– a first step of finding data on cost prices, expressed through unit parameters, of construction or urbanization works similar to those to be estimated;
– a second step of choosing a technical parameter that measures consistency on which to base the comparison with the sample work (for residential buildings, for example, a parameter might be volume, area or number of rooms);
– a final step in which the amount of the previous technical parameter is to be multiplied by the appropriately discounted unit cost, so as to obtain the total reconstruction cost.

Operating in an informal context such as slums, the synthetic-comparative approach (ii) has limitations in the first step of finding data on the cost prices of sample works. Official price lists are often dated and difficult to find. Moreover, the cost items do not always reflect the official ones, as the economic-political environment is highly unstable.

Figure 1 summarizes the steps of the estimation model.

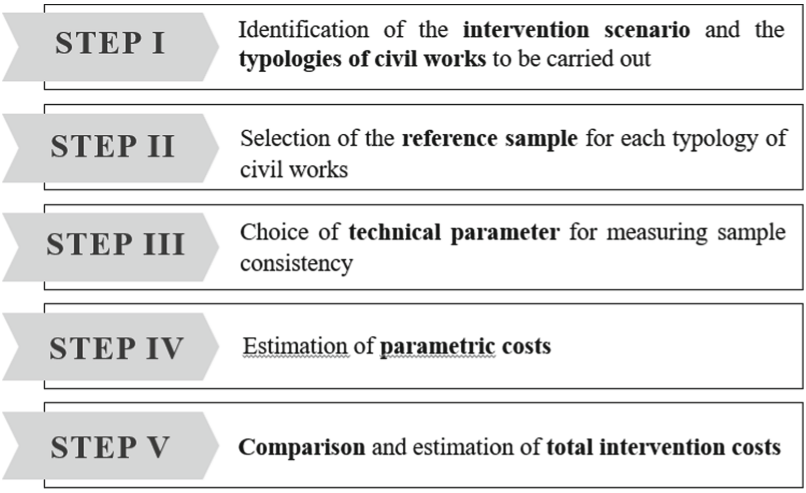

Fig. 1. Steps of the estimation model.

5 Conclusion

Slums are a global phenomenon affecting one billion people around the world, particularly in developing countries. Currently, one in eight people worldwide live in slums or in housing environments with similar conditions; in the next 15 years, it is estimated that more than three billion people will be in need of adequate housing.

Rapid urbanization, migration from rural to urban areas and limited housing options for low-income families are the main causes of slums.

For years, attempts were made to solve the problem by first demolishing most of the slums and later trying to hide them in the suburbs. To date, however, many governments and international organizations have recognized the importance of addressing the slum phenomenon and are implementing policies and programs to provide a future for this substantial part of humanity [38].

Urban redevelopment interventions are a possible solution to improve the living conditions of people living in these areas; however, they can be complex and costly and require careful planning and a multidisciplinary approach involving different stakeholders [39]. Indeed, it is important to make sure that interventions are actually responsive to the needs and requirements of the local communities living in the slums, which is why people are made increasingly involved in decision-making and construction processes.

The economic aspect related to the slum issue is still poorly investigated. The intervention costs for urban redevelopment in these areas can vary depending on the size of the area to be redeveloped, the pre-existing conditions, and the goals to be achieved. Importantly, initial costs, while high, can generate long-term benefits for slum communities and their economic and social development [40].

As a result of the above, the purpose of the work is to define possible intervention scenarios and to characterize a model for the expeditious estimation, through a

synthetic-comparative procedure, of the related construction costs. This makes it possible to provide an economic reference useful in determining the amount of resources to be allocated for urban slum upgrading.

This model has limitations related to the context in which it intervenes.

Slums are characterized by high economic instability resulting from several factors, including lack of job opportunities, low quality of available jobs, lack of access to credit, poor financial services, unstable prices of goods and services, and lack of long-term financial security.

Along with economic instability comes political instability: slums often lack stable and accountable governance structures, and organized crime can play a predominant role [41]. Slum inhabitants often find themselves in situations of social and economic degradation, which can lead to high levels of unemployment, poverty, resource scarcity, and lack of access to public services. This can result in the emergence of criminal groups or paramilitary organizations that seek to control the area and exploit the local population.

The data required to conduct the expeditious estimation of construction costs reflect the instability of the context from which they come and, in addition, are often lacking or difficult to find and require the use of market surveys.

Research prospects involve the application of the estimation model to case studies; this is with reference to the three possible intervention scenarios proposed in Sect. 4: (a) minimal level; (b) barely satisfactory level; and (c) fully satisfactory level. In this sense, the model can also be examined with respect to estimating the costs required to secure socio-economic improvements for communities.

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Blockchain and the General Data Protection Regulation: Healthcare Data Processing

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Abstract. The General Data Protection Regulation (GDPR) of the European Union became binding in May 2018. The objective of the GDPR is essentially twofold. On the one hand, it seeks to facilitate the free movement of personal data between the various EU Member States, and, on the other hand, it establishes a framework for the protection of fundamental rights, based on the right to data protection as set out in Article 8 of the Charter of Fundamental Rights. The European Parliament has declared that the Blockchain must be considered a "tool that strengthens the autonomy of citizens by giving them the opportunity to control their data and decide which ones to share in the register, as well as the ability to choose who can see such data", thus favoring the transparency of transactions. Blockchain (or distributed register technology – DLT) technologies and their potential for the European Union's digital single market have been widely discussed in recent years. It has been argued that blockchain technologies could be a suitable tool to achieve some of the goals of GDPR. Blockchains can be designed to allow data sharing, and improve transparency on data access. This study analyzes the relationship between blockchain and GDPR, to highlight existing problems and study possible solutions in relation to the processing of health data.

Keywords: General Data Protection Regulation · Blockchain technologies · transparency · health data

1 Introduction

Data relating to health are a particular type of personal data characterized by being "related to the physical or mental health of a natural person, including the provision of health care services, which reveal information relating to his state of health". They

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are included in the broader category of data subject to special treatment and enhanced protection, as they are able to reveal very intimate details of the person.

The General Data Protection Regulation (GDPR) of the European Union was created with the aim of harmonizing the regulation on the protection of personal data within the European Union, and of developing the European Digital Single Market, fueling citizens' trust in the use of digital services.

The European Parliament has declared that the Blockchain must be considered a "tool that strengthens the autonomy of citizens by giving them the opportunity to control their data and decide which ones to share in the register, as well as the ability to choose who can see such data", thus favoring the transparency of transactions.

Blockchain techniques, if properly designed, share the same objectives with the GDPR: to create an environment in which data security is guaranteed and to give subjects control over them [1]. Blockchain has numerous benefits such as decentralization, persistence, anonymity, and auditability [2]. Blockchain, originally developed to support the cryptocurrency ecosystem, has recently been used in various other fields to achieve extraordinary levels of security [3]. Similarly, the healthcare sector has started integrating blockchain into various aspects of this digital age. Its features such as micro-transactions, decentralized exchanges, consensus mechanisms, and smart contracts allow for securing the privacy of the health data of patients who are key stakeholders in the healthcare domain [4].

Blockchain applications in the healthcare sector generally require more stringent authentication, interoperability, and record sharing requirements, due to exacting legal requirements [5].

This study analyzes the relationship between blockchain and GDPR, to highlight existing problems and study possible solutions in relation to the processing of health data.

2 The General Data Protection Regulation (GDPR)

2.1 Introduction

The General Data Protection Regulation (GDPR) of the European Union was published in the European Official Journal on 4 May 2016, it entered into force on 24 May 2016, but its implementation took place two years later, starting from 25 May 2018. Since it is a regulation, it does not need to be transposed by the States of the Union and is implemented in the same way in all States without margins of freedom in adaptation.

With this regulation, the European Commission aims to strengthen the protection of personal data of citizens of the European Union and residents, both inside and outside the borders, giving back to citizens the control of their personal data, simplifying the regulatory environment that affects international affairs, unifying and making internal privacy legislation homogeneous.

2.2 Aims and Purposes

The GDPR regulates the processing of personal data of natural persons only and therefore the identification data of subjects with legal personality are excluded from the application of the code.

First, the Regulation provides a definition of "data" or "any information relating to an identified or identifiable natural person (defined as an interested party). The data, therefore, are all the information strictly related to the person. They go beyond the name and surname, including genetic, biometric data and data relating to the health of a natural person.

Furthermore, the GDPR precisely identifies the role and duties of the subjects involved in the protection of personal data, consisting - in addition to the interested party - in the data controller and data processor. In particular:

- the interested party is the physical subject to whom the data refer;
- the data controller is the key figure (natural or legal person, public authority, service or other body that determines the purposes and means of processing) in terms of data protection, because it is this subject to whom the data subject addresses to assert one's rights recognized by the regulation;
- the data controller is the person (natural or legal) who processes the data, responding directly to the owner.

2.3 Relevant Aspects for the Purposes of Health Data Processing

Let's analyze in detail the main articles of the GDPR that may be of interest for the purposes of processing and tracking health data.

Pursuant to art. 2, paragraph 1 of the GDPR:

- *This Regulation applies to the processing of personal data wholly or partly by automated means and to the processing other than by automated means of personal data which form part of a filing system or are intended to form part of a filing system.*

The GDPR applies accordingly to any processing of personal data which takes place in whole or in part by automated means, as well as to processing of personal data which is not automated but forms part of, or is intended to form part of, a filing system.

Personal data processing is defined as 'any operation or set of operations which is performed on personal data or sets of personal data [1].

With regards to blockchains, this very broad definition of what counts as data processing implies that the analysis of personal data, its ongoing retention and any further processing constitutes processing of personal data within the meaning of Article 4(2), of the GDPR:

- *Processing' means any operation or set of operations which is performed on personal data or on sets of personal data, whether by automated means, such as collection, recording, organisation, structuring, storage, adaptation or alteration, retrieval,*

consultation, use, disclosure by transmission, dissemination or otherwise making available, alignment or combination, restriction, erasure or destruction.

Article 3 of the GDPR also provides that:

– *This Regulation applies to the processing of personal data in the context of the activities of an establishment of a controller or a processor in the Union, regardless of whether the processing takes place in the Union or not.*

This implies that where a natural or legal person qualified as a controller or a processor under the GDPR is established in the EU and processes personal data (via blockchain or other means), the European data protection framework applies to such processing. Some data.

The core of the GDPR is the protection of people's data, in other words the individuals to whom that data belongs. In a very synthetic way, this is what the GDPR introduces on the subject in art. 12 and following. Users can:

– *ask and get answers on the use that a company will make of its data and to ask for compensation if these questions do not have clear, concise and timely answers;*
– *know how personal data will be used at the time of their collection/request and know how long they will be kept;*
– *access personal data that are processed/processed by those who have requested consent;*
– *rectify and modify your personal data;*
– *request (and obtain) the cancellation of your personal data when they are no longer necessary for the purposes for which they were collected;*
– *limit the processing of your data (when they are inaccurate, when they were collected illegally or not following legal procedures).*

3 Blockchain Techniques

3.1 Definition of Blockchain

The concept of blockchain was explained by a 2008 paper called Satoshi Nakamoto [6]. Any overview of blockchain technology must commence with the observation that there is not one 'blockchain technology'. Rather, blockchains (or Distributed Ledger Technology – DLT) are better seen as a class of technologies operating on a spectrum that present different technical and governance structures.

DLT is better understood as an inventive combination of existing mechanisms. Indeed, nearly all its technical components originated in academic research from the 1980s and 1990s.

The Blockchain is a technology that "can define a framework of transparency, reduce corruption, detect tax evasion, allow the traceability of illicit payments, facilitate anti-money laundering policies and identify the misappropriation of assets" because it is able to memorize all transactions in blocks connected to each other in chronological order to ensure data integrity. The pillars of this technology are, therefore, the immutability and transparency of data.

The Blockchain, literally "chain of blocks", is a digital register structured as a chain of blocks, concatenated in chronological order, capable of storing data records more commonly called "transactions". The integrity of the blocks is guaranteed using cryptography and one or more transactions can be associated with a block. Furthermore, each block contains a hash pointer linking it to the previous one and a timestamp.

With a previous block hash contained in the block header, a block has only one parent block. It is worth noting that uncle blocks (children of the block's ancestors) hashes would also be stored in Ethereum blockchain. The first block of a blockchain is called genesis block which has no parent block. We then explain the internals of blockchain in details (see Fig. 1) [7].

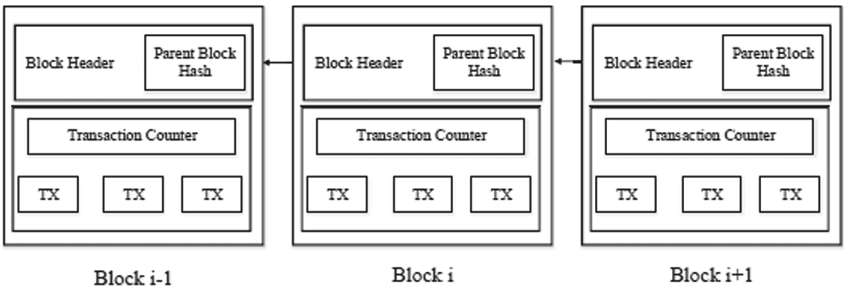

Fig. 1. An example of blockchain which consists of a continuous sequence of blocks [7]

The blockchain is, essentially, an archive divided into different nodes, hierarchically organized: each node can only access certain information and can, if necessary, modify it only by respecting precise and stringent conditions.

In most modern applications and services, the entire system's control lies in the hands of a centralized authority that manages and takes decisions regarding the data being handled [8]. A blockchain enables the decentralization of this control over a network. The blocks are validated using the means of cryptographic hash functions. Each block contains a hashed link to the previous valid block, and this link allows anyone to traverse back through the chain and verify a transaction in the history [9].

The essential components of the blockchain:

- Nodes: are the participants in the blockchain, and are physically made up of the servers of each participant.
- Transaction: consists of data representing the values subject to "exchange" that need to be verified, approved, and archived.
- Block: it is represented by the grouping of a set of transactions that are merged to be verified, approved, and then archived by the participants in the blockchain.
- Ledger: it is the public register in which all transactions carried out in an orderly and sequential manner are "annotated" with the utmost transparency and in an immutable way. The Ledger consists of a set of blocks that are chained together through an encryption function thanks to the use of hashes.
- Hash: a (non-reversible) operation that allows you to map a text and/or numeric string of variable length into a unique and univocal string of a given length. The

Hash uniquely and securely identifies each block. A hash must not allow the text that generated it to be traced back.Nodes or blocks can be of three types:

1. Genesis block/node: it is the hierarchically higher block, from which all the data is made available to the lower blocks;
2. Blocks of the main chain: these are the blocks that are "allowed" to access, use or modify certain information;
3. Orphaned blocks: are blocks that have not been selected for inclusion in a chain.

The data saved on the Blockchain are for this reason considered incorruptible. Each piece of data to be inserted into a block, and consequently each block to become part of a chain, is subjected to a validation process, called mining, in which anyone can participate.

In essence, a blockchain is a shared and synchronized digital database that is maintained by a consensus algorithm and stored on multiple nodes (computers that store a local version of the database).

3.2 Features and Benefits of Blockchain

The main features are:

- Digitization: all transactions are in digital format
- Decentralization: the information contained in the digital register is distributed among multiple nodes (computers that connect to the Blockchain) to ensure computer security so that there is no centralization that the cracker (computer pirate) can exploit to bring down the entire system. The Blockchain also uses public key and private key cryptography;
- Traceability: each element saved in the register is traceable in all its parts and this makes it possible to trace the exact origin and any changes made over time;
- Disintermediation: the individual nodes of the Blockchain certify the distributed information, thus making the presence of central bodies or companies for data certification completely useless;
- Transparency and Verifiability: the contents of the register are visible to all and can be easily consulted and verified. This means that no one can hide or change data without the entire network knowing;
- Immutability of the register: after adding information to the register it is no longer possible to modify it without the consent of the whole network;
- Programmability of transfers: transaction operations can also be programmed over time, so as to be able to wait for certain conditions to occur before proceeding with entry or modification.

The main advantages of systems developed with Blockchain technologies are the possibility of creating a decentralized, shared and immutable archive since, as a rule, its content once written can no longer be modified or eliminated, unless the entire structure.

3.3 Blockchain Technologies for Public Health

Blockchain can also be seen as an agreement convergence algorithm, ensuring that data from books distributed across each node is always present among large nodes. This

ability enables nodes to run anonymously, to have poor connections, or even to involve unreliable operators (see Fig. 2).

Blockchain has many algorithms. We want to apply the health information blockchain using the HyperPORalgorithm, which is an agreement algorithm among public blockchains. The reason for using the Hyper POR algorithm is that these medical data will become a PHR (Personal Health Record) in the future, requiring many TPS (Translations Per Second) if many data are used. This is because many TPS performance data are required to authenticate these blockchains. Therefore, the health information blockchain needs a high-performance consensus algorithm [10].

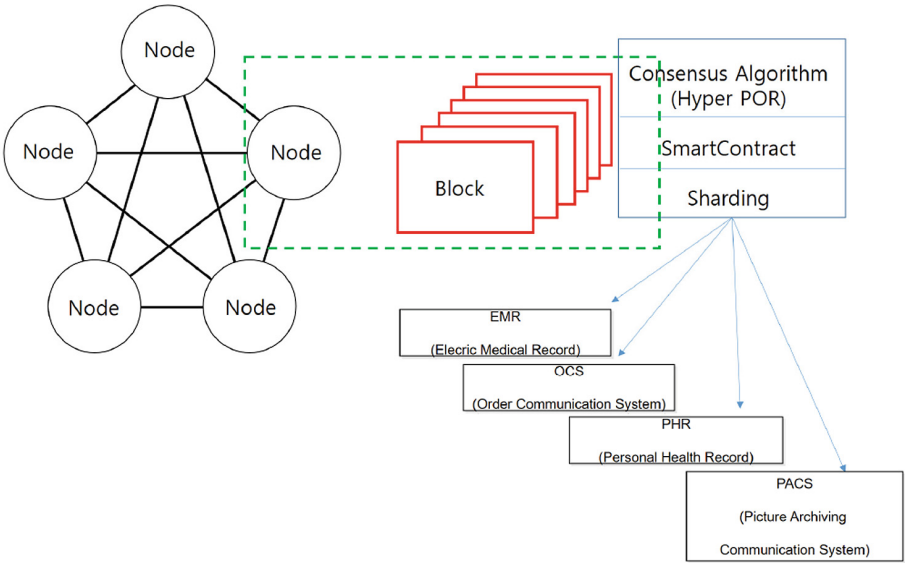

Fig. 2. Blockchain algorithm for healthcare [9]

Different studies suggest the application of blockchain in the health sector mainly for sharing and better management of patient's data, electronic health records (EHR) and, if less frequently, the supply chain management of medical devices and drugs, the management of drug prescriptions, to improve the scientific research and the divulging of scientific knowledge, and for the development of precision medicine [10–16].

Blockchain technology provides numerous benefits to medical researchers, health care providers, and individuals [12,17]. It would serve research as well as personalized medicine to create a single storage location for all health data, track personalized data in real-time and set data access permissions at a granular level [18]. Health researchers need comprehensive data sets to advance understanding of disease, accelerate biomedical discovery, track the development of drugs quickly, and design individual treatment plans based on genetics, lifecycle, and environment [19]. By including patients of different ethnic and socio-economic backgrounds and from different geographic areas, the shared data system of Blockchain would provide a wide range of data set [20, 21]. It provides

perfect information for longitudinal studies because blockchain collects health data over the lifetime of a person [22].

4 Application of the European Data Protection Law (GDPR) to the Blockchain

4.1 Introduction

In recent years, multiple points of tension between blockchain technologies and the GDPR have been identified.

First, the GDPR relies on the basic assumption that there is at least one natural or legal person - the controller - to whom data subjects can turn to enforce their rights under EU data protection law. Data (accountability). Blockchains, however, often seek to achieve decentralization by replacing one unitary actor with many different actors.

Secondly, the GDPR is based on the assumption that data can be modified or deleted where necessary to comply with legal requirements such as Articles 16 and 17 of the GDPR. Blockchains, however, make such data modifications deliberately onerous to ensure data integrity and increase trust in the network (right of the data subject).

Another element of tension between blockchain and GDPR concerns the general principles of data minimization and purpose limitation. While the GDPR requires that personal data processed be kept to a minimum and processed only for purposes specified in advance, these principles can be difficult to apply to blockchain technologies.

Further complexity also relates to the difficulty in determining whether data that was once personal data can be sufficiently anonymized to meet the GDPR's "anonymization" and "pseudonymization".

4.2 Identification of the Data Controller

The first problem that arises concerns the identification of the data controller in the blockchain. The principle of accountability designated by the GDPR is relevant not only in the event of a violation of the law but also in the preventive phase, in which it is up to the owner to choose the "technical and organizational measures" useful for avoiding external tampering.

To identify the data controller in the blockchains, it is necessary to go back to the distinction between private and public. In the former, it would seem easier to identify a data controller, since access is linked to the authorization of certain subjects. Therefore, a sort of centralized government would be replicated that goes well with the prototype designed by the GDPR. The case of permissionless blockchains is different and more complex, where everyone can participate and interact without constraints (peer-to-peer scheme) and it is not possible to find a single control point of the network.

The thesis of those who claim that the data controllers could be the developers of the protocol can easily be overcome: these, in fact, only deal with building a technological infrastructure for other users. According to others, the figure of the data controller would be incorporated by all the nodes of the network: precisely, the node that enters data into the network would incorporate both the user and the data controller, while, if it limits

itself to receiving such data, it would respond only in manager quality. Even this thesis does not remain free from criticisms, mainly concerning the impossibility of fulfilling the principle of accountability in the absence of tools that allow monitoring the use of data.

Finally, some argue that the data controllers are not the nodes, but the users (those who carry out the transactions). In this case, if the user uses the blockchain for personal purposes (not commercial activities) the GDPR under Article 2, paragraph 2, letter c should not apply.

4.3 Rights of the Interested Party

As announced, there are other issues to be examined in the relationship with the blockchain those concerning the founding principles of the Regulation (article 5) and some rights recognized by the interested party.

The first principle is composite since it includes the principles of legality, fairness, and transparency. This assumes that the data controller must have legitimate reasons to collect the data, treating them transparently and without committing illegal activities. If transparency is certainly satisfied in the blockchain, the same cannot be said about the principle of legality, since a user is lawful only when one of the conditions of Article 6 exists. If we take the example of consent, it is natural to ask ourselves who gives consent to the user when it is still uncertain who is the data controller.

Furthermore, they must be "exact, and if necessary, updated" and the owner must implement all suitable measures to promptly modify/cancel the data when this is requested by the interested party. Also in this case, it is not difficult to imagine an incompatibility with the blockchain, given that it is characterized by being a system of adding only, whereby data (even incorrect) remains permanently on all blocks of the chain, without the possibility of modification or cancellation.

The blockchain, by its nature, is destined to grow and cannot regress in any way, and it is precisely the immutability of the data that justifies trust in the network. The non-modifiability of the information is in direct contrast with the data subject's right to rectification and integration. Even if the difficulties in identifying the owner were overcome, this could not in any way modify the block chain. At most, new blocks with adjusted data could be added.

4.4 Data Minimization

The principle of data minimization provides that these are "adequate, relevant and limited" and used only for the stated purposes.

In order to be lawful, and therefore permitted, the processing of "personal data" must be limited only to data that is indispensable, pertinent and limited to what is necessary for the pursuit of the purposes for which they are collected and processed. The reference to the purposes of the collection makes it necessary, from time to time, to ascertain what is the purpose that the Data Controller sets for himself when requesting personal data from the interested parties, since the consent of the latter is, precisely, linked to this sole purpose, and use for different purposes would be excessive and irrelevant.

A collection of data is excessive when it is excessive, exaggerated in numerical terms, too vast with respect to the intention of the person collecting the information; it is irrelevant when it is not linked to the objective to be achieved, it does not serve the pre-established purpose, in summary, it is superfluous.

Only by taking the purpose into consideration is it therefore possible to establish whether the collected data comply with the conditions of lawfulness pursuant to Art. 6 of the GDPR (i.e. if they respect specific, explicit and legitimate purposes), and if their collection is strictly necessary to achieve the set purpose.

4.5 Anonymization and Pseudonymization of Data

Data can be considered anonymous when people are no longer identifiable. However, it should be remembered that a person does not have to be named to be identifiable. In fact, there is a lot of other information that allows an individual to be linked to his personal data and therefore allows him to be identified.

The GDPR, however, does not prescribe any particular technique for anonymization; it is therefore up to individual data controllers to ensure that any anonymization process chosen is robust enough.

On the contrary, it provides that "personal data subjected to pseudonymization, which could be attributed to a natural person through the use of additional information, should be considered as information about an identifiable natural person". Pseudonymization is thus defined as "the processing of personal data in such a way that the personal data can no longer be attributed to a specific data subject without the use of additional information, provided that this additional information is kept separately and subject to technical measures and organizational arrangements designed to ensure that such personal data are not attributed to an identified or identifiable natural person".

The subtle difference between anonymization and pseudonymization has made determining suitable techniques difficult in practice, as demonstrated by several examples of incomplete or incorrectly conducted anonymization processes which ultimately led to the re-identification of individuals.

5 Conclusions

The paper has given a brief overview of how the blockchain system works and the different layers present in the design.

From the analysis just conducted, it has been highlighted that the blockchain is a technology, by definition, incapable of forgetting and resistant to censorship thanks to its widespread data archiving model. It is precisely these characteristics that have determined its rise in recent years, combined with its profound versatility, which makes it suitable for use in many fields.

In recent years we have also seen growing attention toward other needs, equally important and closely connected to the advance of innovation. The protection of personal data is in fact a European (and national) priority even prior to the creation of Nakamoto, which led to the emergence of problems on the applicability of European legislation to

this technological infrastructure and determined the need to find coordination between this and the current regulatory model.

Although some aspects and some rights recognized by the Regulation are not easy to implement, it is clear that there is room for maneuvering to make the blockchain compliant with the requests of the GDPR. Moreover, it must not be forgotten that this regulation and the blockchain have the potential to provide the data subject/user with greater control over their data.

The challenge that awaits us in the coming years concerns the need to find a balance between two European and national needs: to support innovation without forcing it into an inflexible regulatory framework and at the same time guarantee the protection of personal data, including in the face of the advance of new technologies.

In conclusion, it cannot be said that this technology is absolutely incompatible with current data protection legislation, but rather that the use made of it so far has been difficult to coordinate in some cases and for some aspects. However, as already stated, given the enormous potential that exists in the blockchain field, we hope that the legislator will work in this direction.

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A Spatial Statistical Approach for the Analysis of Urban Poverty

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Abstract. The paper analyses the concept of poverty through a multidimensional approach that uses multiple indicators to define a condition of poverty and allows to denote territorial areas and/or population subgroups characterized by situations of hardship or severe social exclusion. This study responds to need of defining and constructing indicators that are capable of estimating poverty in small areas. The complexity of the poverty phenomenon thus poses the need to identify analytical techniques that allow poverty to be framed in a broader context, to improve knowledge of the problem and deal with it through specific economic and social interventions. The data analysed in this paper allowed the construction of three sets of indicators referring to three areas of poverty: economic, social, and housing. The data refer to one Italian region: Apulia. Two methodologies were adopted to study the data. The first based on the Fuzzy approach that uses the technique of Fuzzy Sets to synthesize and measure the incidence of relative poverty in the considered population starting from the statistical information provided by a plurality of indicators. The second, based on a cluster analysis algorithm: the DBSCAN method for identifying dense areas from the fuzzy values processed by the first methodology.

Keywords: Statistical methods; poverty · Fuzzy · DBSCAN

1 Introduction

Poverty analysis is a topic of current interest in both the economic and social fields and is studied as a factor in the evolution and measurement of the level of well-being. In the last couple of years, the interdisciplinary debate on poverty has been growing again due to the adverse conditions in the health field and in the socio-political field, have been done multiple studies with a diversity of approaches. A fundamental prerequisite for a proper statistical analysis of this phenomenon is the need to share an unambiguous definition of the concept of poverty.

The contribution is the result of joint reflections by the authors, with the following contributions attributed to A. Massari (paragraphs 1 and 4), to P. Perchinunno (paragraph 3.2) and to S. L'Abbate (paragraphs 3.1, 3.3), to M. Carbonara (paragraph 2).

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The profound economic and social transformations that have taken place in recent decades place the problem of poverty under a myriad of facets.

Having surpassed the identification of the poor with the person living on the margins of society (such as the homeless), the concept of poverty is extending toward that of economic hardship and social exclusion. This concept, especially in countries with advanced economies, has complex aspects and the theoretical landscape of reference is not unambiguously defined. There is no agreed definition of poverty in the literature. Usually, economic poverty is defined as an insufficiency of resources necessary to ensure a good level of well-being, compared to some predefined standard. In the general sense, assessing poverty means measuring the economic resources of each household and respective individuals against those possessed by other households.

In recent years, efforts have been made to study the problems of income distribution and poverty at the local level but having to deal with severe limitations in data availability and, therefore, resorting to alternative sources, with considerable problems of representativeness of the realities investigated.

2 Poverty Indicators

2.1 Data Sets and Indicators at the Regional Level

As the basis of analysis for the study of poverty, data from one Italian region, Apulia, were analysed focusing on data from "*A misura di comune*" a multi-source statistical information system in which sources of an experimental nature are enhanced alongside more established ones and is the result of the "Measures of well-being and planning at the municipal level" Project launched in 2016. In addition, "A misura di Comune" provides an articulated set of indicators useful for the planning, programming, and management tasks of Local Authorities. The available data provide an understanding of the social, economic, demographic, and environmental conditions of the regional territory, along with measures that reflect the levels achieved in terms of community well-being.

The data available on the "A misura di comune" website are updated to 2015 and the platform is currently being updated. There are 258 municipalities considered at the date of the survey in the Apulia region and they are divided as follows:

41 to the metropolitan city of Bari.
10 to the province of Barletta-Andria-Trani.
20 to the province of Brindisi.
61 to the province of Foggia.
97 to the province of Lecce.
29 to the province of Taranto.

Specifically, several poverty measures were constructed through the analysis of 9 indicators divided into 3 sets for each of the poverty areas identified: economic, social, and housing (Table 1). The indices were chosen to identify levels of economic, social, and housing hardship and were calculated so that high index values corresponded to high poverty levels.

Table 1. Sets of indicators

Set 1 - Indicators related to Economic Poverty
- **Gross disposable income per capita:** ratio of consumer households' gross disposable income to the total number of residents - **Single-income registered households with children under 6 years old:** registered households with at least one preschool child and one income earner per 100 single-income registered households - **Registered households with equivalent income below the social allowance amount**: registered households with equivalent income below the social allowance amount per 100 registered households
Set 2 - Indicators related to Social Poverty
- **Low work intensity of registered households:** registered households with work intensity below 20% of their potential per 100 registered households - **Low work intensity:** percentage of people living in households for which the ratio of the total number of months worked by household members during the income reference year (the one preceding the survey year) to the total number of months theoretically available for work activities is less than 0.20. For calculating this ratio, household members between the ages of 18 and 59 are considered, excluding students in the 18–24 age group. Households composed only of minors, students under the age of 25 and persons 60 years of age or older are not considered in the calculation of the indicator - **High school graduates 25–64 years of age enrolled in the registry:** registered 25–64-year-olds who have completed at least secondary school per 100 persons 25–64 years of age enrolled in the registry
Set 3 - Indicators related to Housing Poverty
- **Housing units reached by Ultra broadband 30 Mb**: housing units reached by Ultra broadband per 100 housing units - In**dex of availability of services in the dwelling: a**rithmetic mean of the individual percentage ratios between the number of occupied dwellings provided with (a) indoor drinking water services, (b) indoor toilet, (c) bathtub or shower and hot water and the total number of occupied dwellings

2.2 Analysis of Data at the Provincial and Municipal Levels

The data available for each municipality were merged at the provincial level in order to analyse them in each of the three identified sets.

Set 1 - Economic Poverty

The higher the value in Table 1 the more the province has a higher level of poverty as found in the provinces of BAT and Foggia for per capita gross disposable income; for single-income households with children under 6 years of age the percentage is higher for the provinces of BAT and Taranto, for the third indicator similarly as income the provinces of BAT and Foggia stand out. In general, for each of the three indicators the provinces of Bari, Brindisi and Lecce are least affected by poverty values.

Confirming what emerges from Table 2, per capita gross income ranges from a minimum of € 6,651.59 for the municipality of Zapponeta in the province of Foggia

to a maximum of € 14,899.06 for the municipality of Lecce for an average per capita gross income of € 997.69. While the percentage of single-income households ranges from a minimum value of 1.14 for the Municipality of Motta Montecorvino in the province of Foggia to a maximum value of 5.99 for the Municipality of Faggiano in the province of Taranto. Finally, the percentage of households with equivalent income below the allowance amount ranges from a minimum value of 10.78 for the Municipality of Sternatia in the province of Lecce to a maximum value of 32.69 for the Municipality of Celle di San Vito in the province of Foggia.

Table 2. Provincial-level indicator values for the first set: Economic Poverty

Provinces	Gross disposable income per capita (inverse with normalized values from 0 to 1)	Percentage of single-income households with children under 6 years of age	Percentage of Registered Families with Equivalent Gross Income below the amount of social allowance
Bari	0.51	3.82	15.98
BAT	0.71	4.30	20.42
Brindisi	0.58	3.40	17.58
Foggia	0.70	3.55	20.94
Lecce	0.60	3.10	18.81
Taranto	0.57	4.11	16.38
Apulia	**0.61**	**3.50**	**18.56**

Set 2: Social Poverty.
The percentage value of high school graduates is lower in the provinces of Bari and Lecce, i.e., those least affected by poverty-related hardships. The provinces with lower literacy are the same with a higher percentage value of unstable and low employment intensity. Thus, social poverty affects the area near Foggia and inland areas the most.

Confirming the findings of Table 3, the percentage of high school graduates varies from a minimum value of 27.95 for the municipality of Lecce in the province of Foggia to a maximum value of 69.05 for the municipality of Zapponeta, the same municipalities that had higher and lower per capita income.

While the percentage of non-stable employed varied from a minimum percentage value of 5.06 for the Municipality of Tremiti Islands to a maximum percentage value of 71.12 for the Municipality of Zapponeta in the province of Foggia.

Finally, the percentage of low employment intensity ranges from minimum value of 20.13 for the Municipality of Cellamare in the province of Bari to a maximum value of 45.31 for the Municipality of Celle di San Vito in the province of Foggia.

Set 3: Housing Poverty.
The percentage values of the index of availability of services in the home are almost

Table 3. Provincial-level indicator values for the second set: Social Poverty

Provinces	Percent High school graduates 25–64 years old enrolled in the registry (inverse)	Percentage Registry enrollees employed not stable in October	Percent Low work intensity of registry households
Bari	46.58	20.22	25.09
BAT	55.51	26.33	29.60
Brindisi	53.36	29.15	28.09
Foggia	52.77	27.01	32.20
Lecce	48.42	20.57	29.65
Taranto	54.26	24.94	28.57
Apulia	**50.47**	**23.42**	**29.28**

equal in all provinces and in any case are very low in all municipalities because all municipalities are reached by the essential services of hot water and sanitation in general. The case for the percentage value of housing units reached by broadband is different; the province of Foggia is always distinguished, which suffers from greater hardship, including housing, and the province of Bari, which, on the other hand, differs from the others in terms of better housing conditions, but also economic and social conditions (Table 4).

Table 4. Provincial-level indicator values for the third set: Housing Poverty

Provinces	Percentage Index of service availability in the home (inverse)	Percentage Housing Units Reached by Ultra Broadband 30 Mb (inverse)
Bari	0.01	8.10
BAT	0.01	12.73
Brindisi	0.01	15.92
Foggia	0.02	69.69
Lecce	0.01	55.68
Taranto	0.02	25.90
Apulia	**0.01**	**43.33**

3 Approaches and Methodologies for Poverty Analysis

3.1 Introduction

Since the 1970s, the various poverty studies have given rise to a variety of approaches, each of which has been matched by careful definition and conceptualization.

A first and more traditional approach is the unidimensional approach. It is essentially based on defining and measuring poverty from a single variable, whether income or consumption.

In most countries, poverty is often analysed using specific common indicators, such as:

– the use of economic variables (income or consumption expenditure);
– the determination of a poverty line, as a dividing line to classify individuals into poor and non-poor.

Thus, the economic connotation of poverty sees, in the first place, the level of consumption and current household income as privileged indicators.

Neither indicator is, however, able to fully exhaust the information needed to construct a measure of poverty, although consumption information is usually preferred because of both the greater reliability of the information collected and the greater stability of the series.

In this context, the many poverty concepts formulated can all be traced back to a traditional distinction between absolute and relative poverty [1, 2].

The approach based on the concept of absolute poverty starts from the definition of poverty as the failure to reach an objective minimum level of well-being and is therefore independent of the social and temporal context. Thus, reference is made to what is known in economic theory as the basic needs approach, according to which poverty is understood as failure to meet basic needs.

The relative poverty approach, on the other hand, is based on the assumption that the social condition of an individual, cannot be defined except from the environment in which he or she lives, i.e., individuals, families, population groups are considered poor when they live in a state of existence worse than the standard of the community to which they belong, i.e., they cannot attain the kinds of food, participate in activities and have those living conditions and comforts that are customary or at least widely encouraged and approved in the society to which they belong.

For the past few years, the subjective approach has been standing crosswise between the relative and absolute approaches. According to the subjective approach, individuals or families who declare themselves to be poor are considered poor in the comparison they themselves make in terms of their perceived well-being with members of the same society. The subjective approach starts, therefore, from the individual's perception of a state of social marginalization.

The presence of a varied range of definitions about poverty means that it is no longer necessary to resort to a single indicator but to a group of indicators useful for defining the living conditions of different subjects, [3–5].

As a result, scientific research options have moved toward the establishment of a multidimensional approach, sometimes abandoning dichotomous logic, and going as far as fuzzy classifications in which, each unit simultaneously belongs and does not belong to the category of poor.

A multidimensional index, which considers poverty as an overall condition of backwardness and deprivation and analyses relative poverty within the living standards of the target population, seems the most appropriate tool from the perspective of differential socioeconomic analysis of demographic phenomena.

The approaches used to arrive at synthesizing and measuring the incidence of relative poverty within the population under consideration are the Totally Fuzzy and Relative method and DBSCAN method. The first method uses the technique of Fuzzy Sets (Fuzzy Set) to obtain a measure of relative poverty incidence within a population from the statistical information provided by a plurality of indicators; the second is a method of clustering territorial units to obtain areas of high (or low) intensity of the phenomenon that allow the aggregation of contiguous spatial units homogeneous with respect to the phenomenon under study.

To overcome the limitations of the traditional approach, therefore, it is necessary to broaden the analysis to include a wide range of indicators of living conditions and at the same time to adopt mathematical tools to adequately account for the complexities and vague nature of poverty.

3.2 The Fuzzy Approach

The development of fuzzy theory initially stems from the work of Zadeh [3] and subsequently was conducted by Dubois and Prade [6]. The fuzzy theory develops starting from the assumption that each unit is not univocally associated with only one but simultaneously with all the categories identified based on links of different intensity (degrees of association).

The first measurement based on the fuzzy set theory, named TF (Totally Fuzzy), was suggested by Cerioli and Zani [7]. This logic can be applied to both continuous and ordinal variable cases. However, in the latter case, the maximum and minimum values can be determined by assuming the value of the lowest category as minimum and the highest as maximum.

Cheli and Lemmi [8] have proposed a generalization of this approach, called Totally Fuzzy and Relative (TFR). This method is also called "totally relative" because the value of the membership function is entirely determined by the relative position of the individual in the distribution of the population. The fuzzy TFR approach consists in defining the measurement of an individual's degree of belonging to the totality fuzzy, included in the interval between 0 (with an individual who does not demonstrate a clear belonging) and 1 (with an individual who demonstrates a clear belonging).

If we suppose to observe k indicators for each family, the function of belonging of the i-sima family to the blurred subset, can be defined as follows [8]:

$$f(x_{i.}) = \frac{\sum_{j=1}^{k} g(x_{ij}) \cdot w_j}{\sum_{j=1}^{k} w_j} \qquad i = 1, \ldots\ldots, n \tag{1}$$

where $w_1,\ldots,w_k$ represent a generic system of weights. The $f(x_{i.})$ is in practice a global poverty index, while $g(x_{ij})$ measures the specific deprivation of the i-sima unit according to the j-th indicator. Following the Totally Fuzzy and Relative Approach (TFR) proposed in [6] the function $g(x_{ij})$ is defined in terms of the partition function H (•) of the indicator X_j as follows:

$$g(x_{ij}) = \begin{cases} H(x_{ij}) & \text{if the risk of poverty increases with increasing of } x_j \\ 1 - H(x_{ij}) & \text{if the risk of poverty decreases with increasing of } x_j \end{cases}$$

The indices were chosen to identify different levels, related to aspects of poverty [9, 10]. The indices were grouped into three sets characterized by different situations in the different components considered: economic poverty, lack of basic services, lack of housing-related services.

The Totally Fuzzy and Relative method was applied on the data of all the Italian regions obtaining a value of the individual w_i weights, which varies according to the level of importance in determining the degree of quality of the situation.

The indicators were chosen to identify the different levels, related to the aspects of poverty, and grouped in the three described sets characterized by different situations in the different components considered: economic, social, and housing poverty. The Total Fuzzy and Relative method was applied on the data of all the Apulian municipalities obtaining a value of the individual w_i weights, which varies according to the level of importance in determining the degree of quality of the situation.

Minimum, maximum, and average values were calculated for each indicator of the different sets. For each set of indicators, the fuzzy value and its related values were calculated. As a result of the application, we classified the Apulian municipalities based on the fuzzy values obtaining the classification shown in Table 5. High values are significant of municipal situations of poverty, vice versa low values are significant of situations of no hardship.

Table 5. Absolute and percentage composition of municipalities by membership in fuzzy classes

Fuzzy values	Number of municipalities			%		
	SET 1 Economic hardship	SET 2 Social hardship	SET 3 Housing hardship	SET 1 Economic hardship	SET 2 Social hardship	SET 3 Housing hardship
0,0 ⊣ 0,2	0	14	127	0	5	49
0,2 ⊣ 0,4	29	48	72	11	19	28
0,4 ⊣ 0,6	84	40	22	33	16	9
0,6 ⊣ 0,8	139	91	8	54	35	3
0,8 ⊣ 1,0	6	65	29	2	25	11
Total	**258**	**258**	**258**	**100**	**100**	**100**

In particular, the percentage of municipalities with high economic hardship (fuzzy value between 0.8 and 1) appears to be smaller (2%) than the percentage representing social hardship (25%). Two of the largest percentage values (54%) and (35%) represent high economic and social hardship, respectively (fuzzy values between 0.6 and 0.8) compared to a percentage of 3 percent of municipalities with high housing poverty.

Going to graphically represent the different sets of indicators yields the following cartographies: darker colours refer to the highest values and thus to the municipalities with the greatest difficulties.

As for the set related to economic poverty indicators, the municipalities with high difficulties are only 6: Andria, Barletta, Bitonto, Lucera, Sannicandro di Bari and Trinitapoli (fuzzy values between 0.8 and 1), to which are added the 139 municipalities with high values (fuzzy values between 0.6 and 0.8) that are distributed in the area near Foggia, inland of Bari and Taranto (Fig. 1).

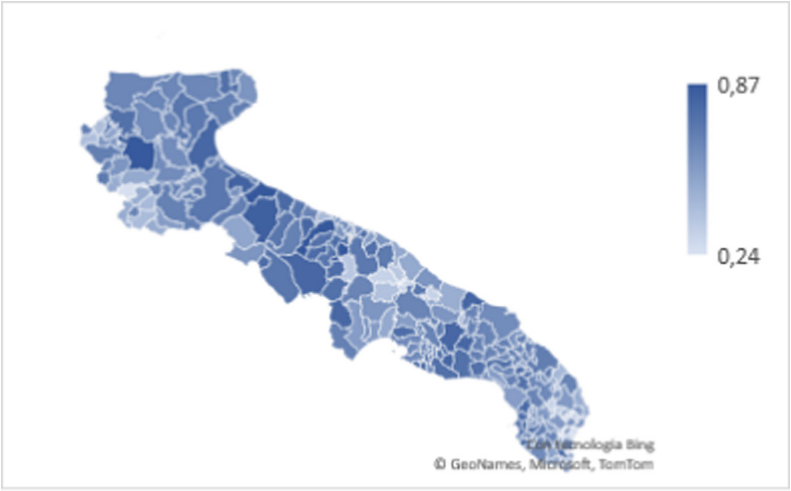

Fig. 1. Spatial Distribution-Economic Poverty (Fuzzy Values)

Relative to social hardship in high hardship (values between 0.8 and 1) and hih hardship (values between 0.6 and 0.8) there are 65 and 91 municipalities respectively distributed among the provinces of Foggia, BAT and Taranto. (Fig. 2).

Finally, regarding the lack of housing-related services (Fig. 3) there are 29 municipalities with problematic situations located mainly in the hinterland of Foggia and Brindisi (values between 0.8 and 1). Most Apulian municipalities do not experience housing problems at least in terms of the indicators considered because almost all homes are now reached by the essential services of drinking water, toilet, bathtub or shower and hot water, as well as Ultra Broadband.

3.3 The DBSCAN Approach

The fuzzy approach responds to the need to identify spatial areas and/or population subgroups characterized by situations of hardship or high social exclusion because it allows a measure to be defined of the degree to which they belong to the fuzzy set of the deprived. It is possible to employ methods of clustering territorial units to obtain areas of high (or low) intensity of the phenomenon by using clustering methods that allow the aggregation of contiguous spatial units homogeneous with respect to the phenomenon under study. Hence the need to supplement the fuzzy approach with one based on DBSCAN.

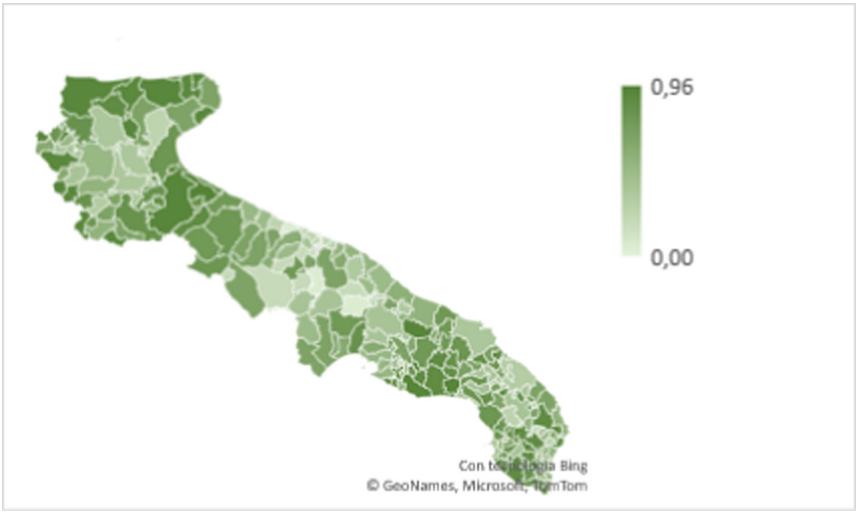

Fig. 2. Spatial Distribution-Social Poverty (Fuzzy Values)

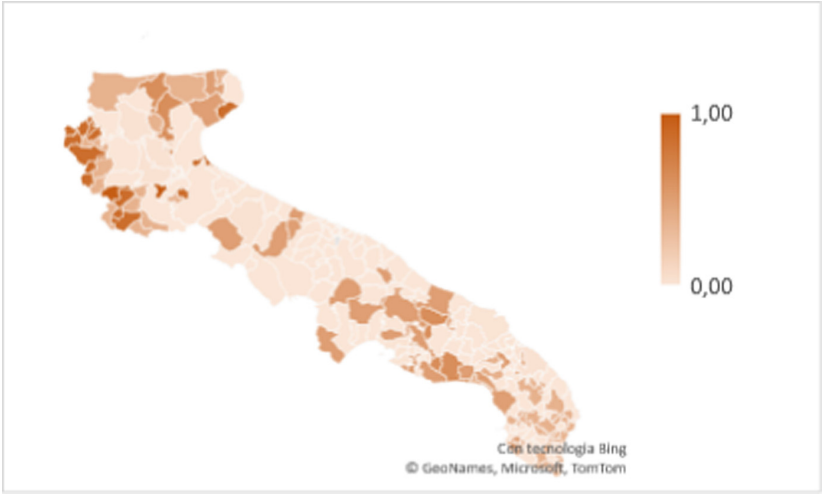

Fig. 3. Spatial Distribution-Housing Poverty (Fuzzy Values)

DBSCAN (Density Based Spatial Clustering of Application with Noise) [11], was the first clustering method based on spatial density. The basic idea is to define a new cluster or extend an existing cluster, the surroundings of a point of a given radius ε, must contain at least a minimum number of MinPts, i.e., the density of the points must exceed a certain threshold. DBSCAN as input needs the parameters ε and MinPts to be fixed. Their choice is crucial since they determine whether a group of points is a cluster or simply noise.

The authors in this regard provide a heuristic that they consider sufficiently valid. Let d denote the distance of a point p from its k -th nearest neighbour; within a distance d from p are then contained k + 1 points (barring special cases in which multiple points are at the same distance d from p). Having fixed k, we define a k -dist function, from the dataset D to the set of real numbers, that assigns to each point in D the distance to its k -th nearest neighbour. Then the points in the dataset are sorted in descending order with respect to k -dist, resulting in a graph called the sorted k -dist graph.

This graph provides information about the density distribution of the dataset: in particular, by choosing an arbitrary point p and fixing MinPts to k and ε to k -dist(p), all points having equal or lesser k -dist will be core points.

Having chosen a threshold point on the graph, to which corresponds a value of k -dist and hence ε, all patterns preceding it turn out to be noise while those following it will be assigned to clusters. The authors recommend choosing as a threshold the point at the first re-entrant that can be seen in the graph's trend; Such determination of ε has ambiguities within it since the graph does not have a sharp dip but often fluctuations are evident so the choice of ε is reduced to a trial-and-error choice of the most appropriate one.

The DBSCAN algorithm has been applied to municipalities to aggregate them even from different provinces to find spatially close and contiguous areas with similar characteristics to better organize spatial planning.

The municipalities were aggregated through the DBSCAN algorithm, based on the fuzzy value.

To define the optimal value of ε, the k nearest neighbour distances in a matrix of points were calculated. The idea was to calculate, the average of the distances of each point to its k nearest neighbours. The value of k was initialized equal to the same value of MinPts.

Next, these k-distances were plotted in ascending order, and the goal was to determine the inflection point corresponding to the optimal parameter. Figures 5, 7 and 9 show plots of the k-distances for each of the three sets of indicators, and the optimal value that was empirically chosen to assign to ε is highlighted. Increasing even slightly the value of ε concentrates the points into a single cluster, while decreasing the value of ε increases the noise points and increases the clusters.

The three cartographies in Figs. 4, 6 and 8 show in yellow the noise points, i.e., those not classified by the algorithm.

Specifically, the first cartography, Fig. 4, was processed by assigning the values obtained with the DBSCAN algorithm having assigned ε value 0.14, MinPts value 3 and using the fuzzy values of the first set of indicators related to economic poverty. Ten clusters highlighted with the various colours were obtained. The clusters formed by the municipalities with a higher fuzzy value and spatially close are those highlighted by the orange and yellow ochre colours and the blue corresponding to the areas of the provinces of Foggia and Taranto.

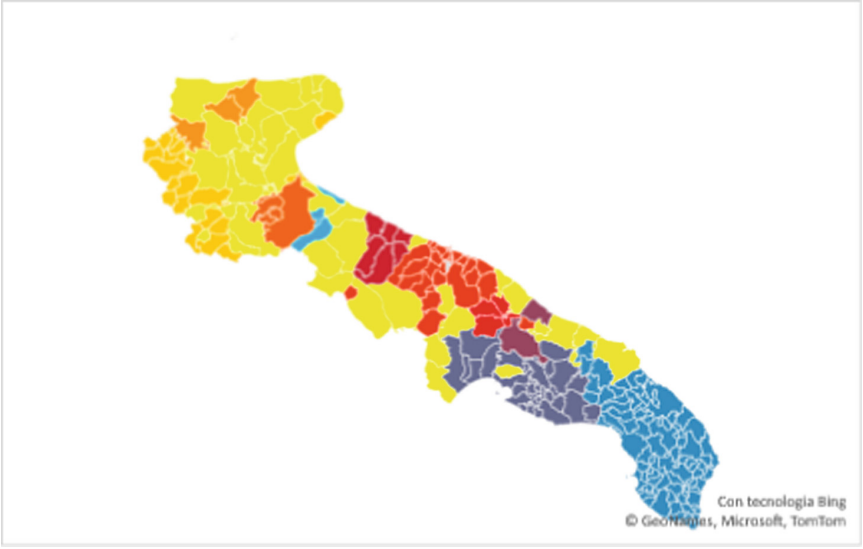

Fig. 4. Identification of dense areas with DBSCAN: Economic Poverty ($\varepsilon = 0, 14$ and MinPts = 3)

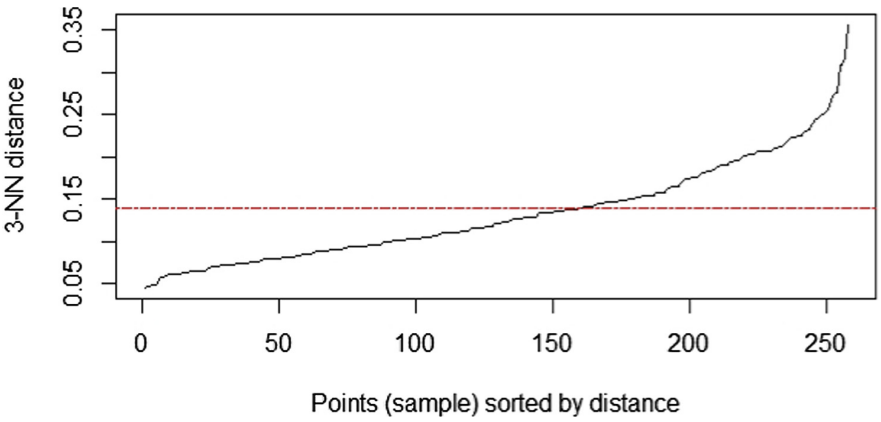

Fig. 5. Graph of k-distances for $\varepsilon = 0, 14$

The second cartography, Fig. 6, was processed by assigning the values obtained with the DBSCAN algorithm having assigned ε value 0.176, MinPts value 3 and using the fuzzy values of the second set of indicators related to social poverty. Thirteen clusters were obtained, those formed by municipalities with a higher fuzzy value and spatially close are highlighted by orange and the yellow ochre and the blue colors corresponding to the areas of Foggia, Brindisi and Taranto.

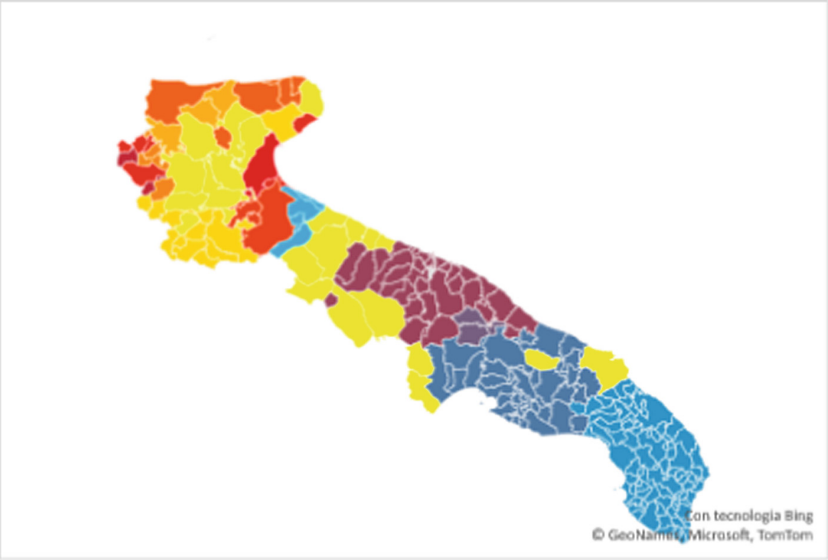

Fig. 6. Identification of dense areas with DBSCAN: Social Poverty ($\varepsilon = 0,176$ and MinPts $= 3$)

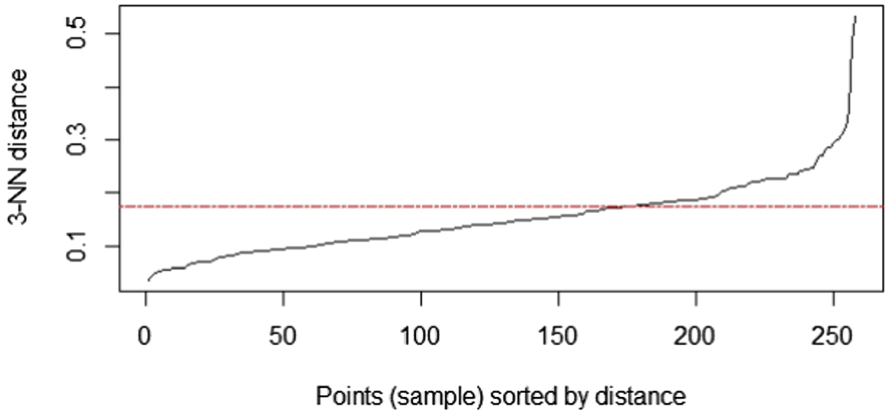

Fig. 7. Graph of k-distances for $\varepsilon = 0,176$

The third cartography, Fig. 8, was processed by assigning the values obtained with the DBSCAN algorithm having assigned ε value 0.17, MinPts value 3 and using the fuzzy values of the third set of indicators related to housing poverty. 11 clusters highlighted with the various colors were obtained, those formed by the municipalities with a higher fuzzy value and spatially close are those highlighted by the red and blue colors in the areas of Foggia and Brindisi respectively.

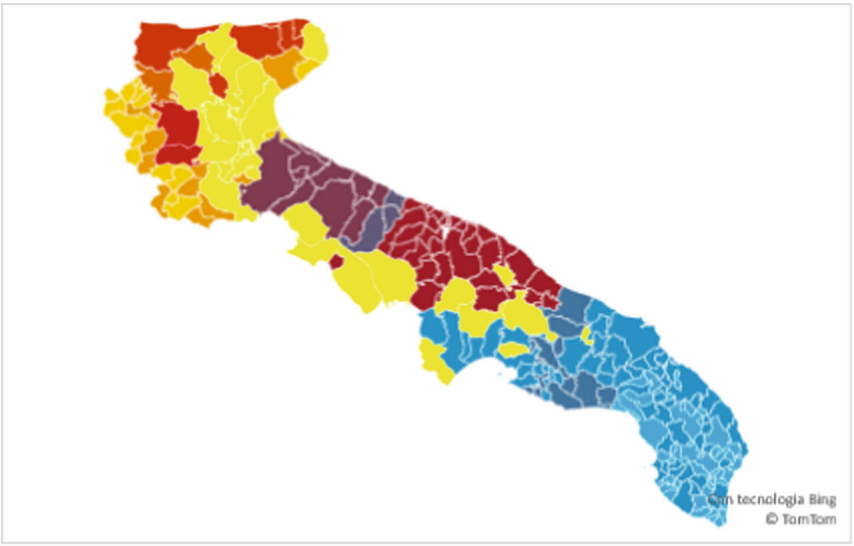

Fig. 8. Identification of dense areas with DBSCAN: Housing Poverty ($\varepsilon = 0,17$ and MinPts $=$ 3)

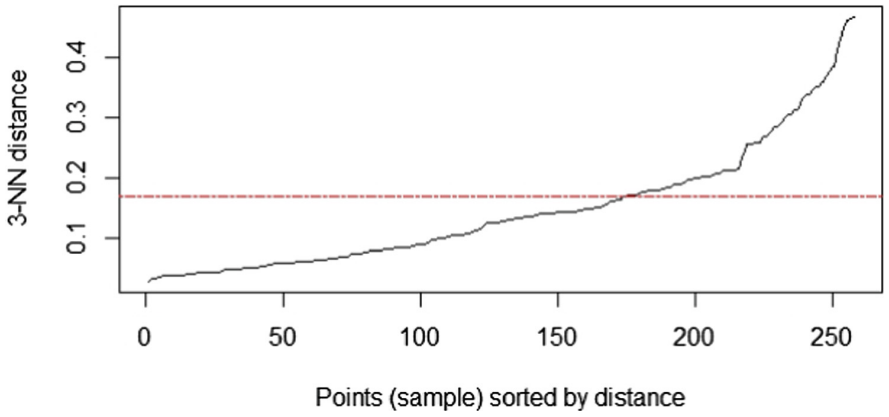

Fig. 9. Graph of k-distances for $\varepsilon = 0,17$

4 Conclusions

Poverty connotes a hardship that does not necessarily end in the lack of monetary resources but involves a plurality of dimensions of a social and cultural nature such as education, health, housing, and is embodied in the lack of equitable access to a plurality of essential goods and services.

In both academic literature and international scientific reports, however, the multidimensional nature of poverty is emphasized, implying the need to use not a single indicator but a group of indicators, which are useful in better delineating the living conditions of different individuals.

A first idea that emerges from this work is related to the ability to describe territorial phenomena through an integrated model, which starts from the construction of socioeconomic indicators, which are multidimensional in nature, and then adopts models capable of identifying areas at risk of hardship through statistical methods [12–14].

In this way, as with the data studied in this paper, it is possible to assess the problematic aspects that characterize households in a specific historical, geographical, and social context, as well as to assess socioeconomic distress, identify the profiles of new poverty and the impact of poverty on public institutions. In fact, the results presented in this paper from the fuzzy and DBSCAN approaches show that almost always the same are the provinces that need more attention from local policies. Targeted government action would be needed to support these areas. Certainly, to reduce poverty, it is necessary to ensure equal rights, access to economic and natural resources, technological resources, property, and basic services.

Future research developments may address other urban topics (such as real estate market and housing conditions) in order to highlight other useful issues through a spatial analysis of different sources of indicators as shown in [15, 16].

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Short-Term Island: Sharing Economy, Real Estate Market and Touristification Interplay in Capri (Italy)

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Abstract. Digital platforms and the sharing economy are influencing the socio-spatial dynamics of cities, generating new behaviors and uses, promoting new opportunities, and bringing to light many critical issues related to, for example, the real estate market and social inequalities. The short-term rental website Airbnb is a relevant example of how online intermediaries can reshape urban practices, change social and cultural relationships, damage the traditional real estate market, and accentuate spatial hierarchies and inequalities. In this process, touristification represents an emerging crucial issue and a challenge for public policies oriented towards supporting the development of economic drivers and reducing social injustices. The social and economic fabric of entire neighbourhoods changes to accommodate tourists, progressively replacing local residents and activities. Territories are severely damaged and polluted due to intensive resource exploitation, and historic centres are being depopulated while becoming overcrowded with tourists. Tourism, if not well managed and thus in the absence of a clear and long-term vision, can produce negative effects on the urban system. This study, developed under the PRIN Research Project "Short Term City. Digital Platforms and Spatial Injustice", aims to analyse the effects of short-term rentals and the related "touch and go" tourism on the cities. In particular, the focus is on Capri Island, Italy, and on the comparison between the Airbnb rental market and the "ordinary" real estate market. In this framework closely linked to "touch and go" tourism, a new online platform (called Inside Capri) is proposed, based on the logic of sharing and collaboration in line with circular economy principles. This platform aims to valorize local cultural heritage and promote cooperation between tourists and the community to make the tourism sector more sustainable.

Keywords: Sustainable Cultural Tourism · Real Estate Market · Digital Platform

1 Introduction

The capacity of digital media to connect information, places and people is propelling us into a dimension that could be described as hyper-connected: whatever lens used to look at social networks, whether anthropological, sociological or economic, it is clear that

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this state of total dependence provides many benefits but, at the same time, also many disadvantages.

The sharing economy has grown exponentially since 2008, following the great financial (and then economic) crisis, and has been supported by a wave of major technological innovations. It is the driving force behind every idea related to new changing markets and needs, characterized by powerful technologies but still undefined objectives, and a fragile balance between tangible and intangible values and assets [1].

Although the phenomenon was identified by Lessing in 2008 [2], it was only in 2012 that Botsman and Rogers [3] used the expression "collaborative consumption" to describe the emerging sharing economy. They highlighted the specificities of this growing phenomenon, which is likely linked to the convergence of opportunities offered by digital media with economic, cultural, and social changes of the period. From a macroeconomic point of view, the assumption falls within the definition of the hybrid models of the circular economy [4], in which nothing is waste, and everything is reintroduced into the loops, becoming a resource. In the sharing economy, the transfer of ownership over tangible and intangible assets occurs among the parties of a transaction. With the progressive appearance of profit-related components, at the expense of solidarity nature and social interaction at the heart of the phenomenon, intermediation platforms have emerged, forcing the collaborative economy to compare regulatory, deontological and cultural issues. The efficiency generated by platforms extends to the entire economy [5].

The impacts of the sharing economy's growth on the environment, social system income distribution, and employment are often contradictory: platforms have the potential to damage traditional tourism markets and result in a loss of permanent jobs that cannot be fully balanced by corresponding increases in flexible and temporary jobs created by these platforms [6]. The net distributional effect of the income-generating activities of the sharing economy may increase or decrease inequality, depending on how these benefits are distributed across different social classes. Platforms economies and the sharing economy represent two forms of economy that are significantly shaping the development of tourist activities, triggering new dynamics in the relationship between demand and supply in the short-term rental market [7].

Among the examples of platforms that have developed increasingly relevant processes and services, Airbnb offers (since 2008) an online platform that connects hosts of homes and rooms for rent with guests looking to rent.

The platform's role is to facilitate the research for availability of homes and rooms and to be an intermediary for payments. The website is funded by a commission on each rental, which varies between 6–12% of what the guest pays and 3% of what the host receives.

The proliferation of Airbnb took place in a context of economic recession, job insecurity, shrinking wages, rising costs of living [8].

The Airbnb strategy is based on establishing a rental gap, which is the difference between the actual capitalized value and the potential value of an area [9]. Airbnb creates the gap as a tool to increase the real value of rents, and then fills it by increasing the value of the whole area [10, 11]. This creates a dynamic of gentrification and tourism in historic centers and has significant negative effects on the cities where the platform operates [12].

Airbnb is therefore partly responsible for a shift in scale: it is a tool to accumulate profits and concentrate wealth in the hands of a few absentee owners who rent out houses to "touch and go" tourists [13], driving up property values and rents, concentrating the supply of rental housing and thus displacing the middle and lower classes from urban centres [8].

The increase in inequality and wealth concentration is leading to the selective development of urban areas and the exclusion of low- and middle-income families from access to home ownership or rental housing [14]. Financial housing market, encouraged by the abandonment of public housing policies and the reliance on the free market for housing solutions, have caused unprecedented levels of displacement. Homes have become repositories of wealth. Meanwhile, the number of empty homes and homeless people is increasing. In the last decade, a new phenomenon has been added to the process of gentrification: tourism and the replacement of a resident population with a temporary one.

The limited capacity of politicians to read the new urban phenomena and the new housing discomforts, the active promotion of tourism as an engine of growth for cities, also through an improper use of cultural heritage, and urban renewal projects in a private key, are the source of the market's unsatisfied housing demand [15, 16].

If the mantra is that "tourism generates wealth", one must ask "for whom": tourism doesn't benefit the inhabitants struggling with the collapse of local public services; it doesn't benefit the city, whose historical and cultural heritage is reduced to a backdrop and venue for major events [8].

This research is part of the PRIN research programme "Short Term City". After investigating the general effects from the Airbnb development, it aims to answer some questions, focusing on the analysis of this phenomenon in Capri Island (Italy). The main questions are: How does the proliferation of Airbnb on Capri Island affect the quality of life of its inhabitants and their rights related to housing and work? How does this phenomenon affect the traditional market of buying and renting? What is the impact of uncontrolled tourism development on the island's natural heritage and historical and cultural identity? Is it possible to develop a sustainable tourism model that preserves history, the environment, the community and the economy?

The article is organized as follows: in Sect. 2 the case study, the Capri Island in Italy, is presented, focusing on the tourist vocation of the place; in Sect. 3 the methodological approach of the research is described; in Sect. 4 Capri and Anacapri short-term rental market dynamics are analysed and compared with the "traditional rentals". Then, on the basis of the critical analysis of the above investigation, a new platform to make the tourism sector more sustainable is proposed. Section 5 draws summary conclusions.

2 The Case-Study

Located in the southern part of the Gulf of Naples (Italy), Capri Island is an island in the Tyrrhenian Sea with an area of 10.3 km^2. Administratively, the island is divided into two municipalities, Capri and Anacapri, with a total population of 12,112 inhabitants (Fig. 1).

Island's popularity dates to Roman times, with the arrival of the emperors Octavian and Tiberius. Known as a Grand Tour destination in the 19th century, the Island became an

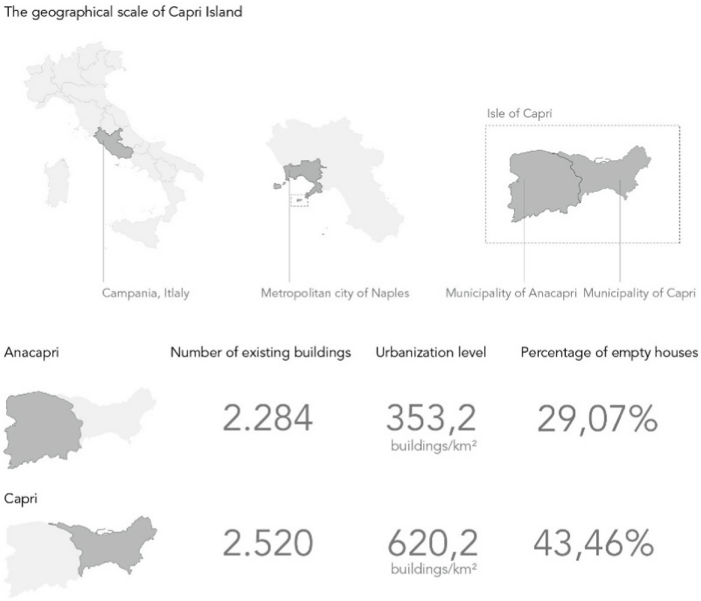

Fig. 1. Case study (data source www.borsinoimmobiliare.it)

international meeting place for artists from the mid-20th century, developing a distinct art of reception. This resulted in the progressive decline of agriculture and coral production in favour of tourism, still the most important driving force of the island.

In addition to Italian tourists, the Island is a strong attraction for international tourism: Brazilians, Japanese, Koreans and Russians are just some of the most frequent visitors. The heterogeneity of visitors is also reflected in the type of tourism generated and in the distribution of flows. In fact, three main types of tourism can be distinguished: the "touch and go" type, in which the stay, which does not exceed eight hours, is concentrated in the area of the Marina Grande, the port area of the Island. Alternatively, groups of these tourists are offered bus or boat tours of the Island. A type of "worldly" tourism that is more focused on the town of Capri, the more famous side of the Island, known for its luxury shops, nightclubs and the famous Piazzetta. In this case, the length of stay can vary from 2 to 5 days. Finally, there is "slow" tourism. This is a niche type of tourism that focuses on an in-depth experience that allows you to immerse yourself in the ecosystem of the place. This type of tourism is particularly attractive for the town of Anacapri, which is the opposite of Capri: simpler, with a more private and discreet ambience, but also full of beautiful sights.

If Anacapri has always been less touristy than Capri, it has also been hit by the massive influx of tourists in recent years, which is why the study reports distortions in the property market.

3 Materials and Methods

The methodology used was based on the exploration and analysis of websites and online platforms to understand the impact of the development of Airbnb Capri Island. The data gathered and organized were then analysed and assessed in order to provide a relevant knowledge framework to identify appropriate solutions for a more sustainable tourism [15, 17]. The methodology has been structured in the following phases (Fig. 2):

1. Research and data collection from Airbnb platform to provide a general overview of the dynamics of the real estate market related to the above platform (in Capri and Anacapri);
2. Analysis and extraction of data from www.airdna.com for an in-depth study of short-term property market dynamics in Capri and Anacapri;
3. Analysis of the "traditional" real estate market dynamics in Capri Island and comparison with Airbnb market.
4. Proposal of a knowledge sharing platform for a more sustainable tourism in Capri Island.

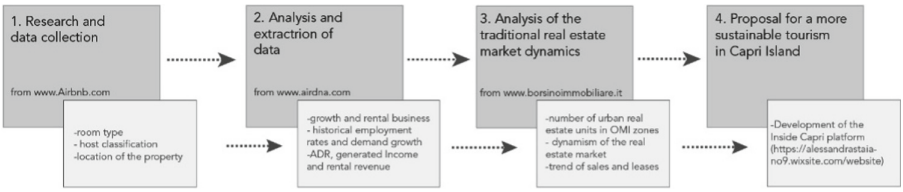

Fig. 2. Methodological framework and steps

In the first phase, in order to provide a snapshot of Capri Island after the development of the short-term rental market, an analysis of the most interesting aspects of the Airbnb website was carried out through a consultation during a limited period of time between June and July 2021, including:

Type of listing: Airbnb hosts can rent out entire apartments, private rooms, or shared rooms. Depending on the type of accommodation offered, a listing can function more like an unregulated hotel. It can produce negative impacts on the neighbourhood, take housing away from the housing sector, and be illegal.
Classification and origin of the host: A host who has one or two listings for an apartment/room on the platform can be considered a private individual. However, it is possible that hosts with multiple listings are run as a real business and do not live in the property itself, thus violating the terms of the short-term rental regulations designed to protect the accessibility of the housing market. For each listing found, the number of listings held by each host and their origin, where this could be deduced from the biography provided, were also examined.
Location of the property: this was useful for an understanding of which parts of the Island had more supply than others. After obtaining the data on the mapping of suppliers, they were distributed in the different zones identified by the Island's Property Market

Observatory. The real estate zone reflects an area of the local real estate market where there is a substantial uniformity in the assessment of economic and socio-environmental conditions. The Agenzia delle Entrate has identified the following zones for Capri Island: B (B1/B2); D (D2/ D3/D4) ed R (R1). This will then be used to calculate the ratio between the number of Airbnb listings and the number of properties per OMI zone, to quantify how widespread, the phenomenon is in the area.

In the second phase, after obtaining an overview of the whole Island, information provided by the AirDNA website (www.airdna.com) have been analysed. The system servers collect booking data for each Airbnb listing on a daily basis. The information studied ranges from daily calendar prices to cancellation policies and booking times, and the data are extracted using a variety of servers: a scrape of data from Airbnb and Vrbo is made; a matching algorithm is used to take account of dual-listed properties; bookings are tracked according to the blocked or booked methodology; and the Market Minder and company data are updated. The data from these sources is 100% accurate and based on actual bookings. AirDNA's ability to develop such accurate models is made possible by extensive historical surveys that have been collecting actual data for years. The most useful of these includes growth and rental activity, demand growth, income generated and rental income.

In the third phase of the research, the dynamics of the ordinary real estate market on Capri Island has been analysed, using information obtained from the Agenzia delle Entrate and the Borsino Immobiliare regarding the presence of urban real estate units in the various OMI zones, the dynamics of the real estate market and, consequently, the trend in sales and rentals. The evolution of the prices of properties for sale and rent on the Immobiliare website (www.Immobiliare.it) was then analysed.

The aim was to understand whether and to what extent renting a property on Airbnb is more economically advantageous compared to offering it on the traditional rental market, and how the damage of the traditional market affects the lives of residents and contributes to the growing tourism in the area.

The study has been carried out in September 2021, the first year after the pandemic, and updated in April 2023.

4 Results

4.1 Capri and Anacapri Short-Term Rental Market Dynamics

In April 2023, the number of active advertisings on Capri Island was 776. This is an increase of 14.12% compared to 2021, when the total number of active ads was 680. Active listings are those that have been booked or available for at least one day in the last month. The distribution of the differentiated supply (entire home, private room, shared room) in Capri and Anacapri is showed in the Fig. 3, Fig. 4.

A first reflection emerged from the data in the above figures is that Capri has the largest share of the short-term rental market, with 445 active listings. This highlight that Capri is more active touristically than Anacapri.

It can also be assumed that the nature of tourism tends to be slightly different between the two municipality: while Anacapri has an almost homogeneous supply in terms of

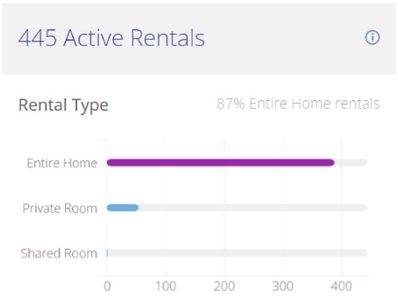

Fig. 3. Active Rentals in Capri

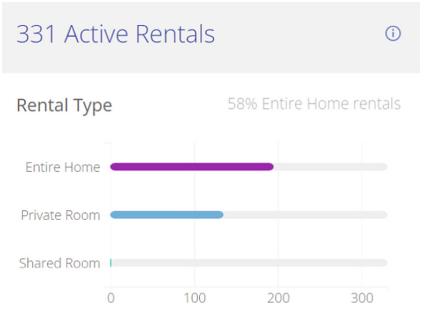

Fig. 4. Active Rentals in Anacapri

distribution between whole apartments and private rooms, in Capri 87% of the supply is represented by houses and apartments. Contrary to Airbnb's claim, this significant percentage shows us that these are not shared spaces, but apartments that generate extra income in houses where no one lives. This is confirmed by the statistics from www.borsinoimmobiliare.it, which show a very high percentage (43.46%) of empty houses or second homes in the municipality of Capri. Far from being a casual activity, renting out an apartment or rooms to generate income is therefore a real entrepreneurial activity.

Only 208 advertisings, 30% of the total, turn out to be managed by hosts can be considered as private. The presence of multi-hosts, and therefore agencies, is evidence that platforms are only ostensibly disintermediation devices. The presence of multi-hosts, and therefore agencies, is proof that platforms are only seemingly disintermediation devices. The rhetoric of sharing promoted by Airbnb clashes with the evidence of an extremely unequal income distribution, given that hosts with more than one listing represent the largest share of the market generated by rentals on Airbnb. Moreover, in relation to the 412 hosts found, the analysis of the data about origin that can be extracted from the biographical-descriptive section of the host, linked to the unique name of some advertisements, has shown that a large part of them do not live permanently on the Island, but the properties available for short-term rentals come from people who have inherited them from their families and now find themselves managing them, thus taking them away from the usual rental or sales market. The contradiction between the platform's slogan and the way it is actually used seems clear: what Airbnb propagates as "unused rooms offered by locals, offering warm hospitality at an affordable price for young people travelling the world on a budget" has become a real business.

The listings are divided as 23% and 26% respectively in OMI zones B1 and B2, which are the core zones. In D3/4 zone this percentage is 34%, while in zone D2 it is only 18%. However, as shown in Fig. 5, despite the difference in size between areas defined as peripheral and central, most of the listings are located in historic centres. Airbnb listings tend to be concentrated in historic centres, gentrified neighbourhoods and adjacent areas, and not, as the platform's rhetoric suggests, in peripheral areas that tend to be excluded from tourist traffic.

It is interesting to compare Capri and Anacapri with respect to the Market Grade. The Market Grade is a way of ranking the performance of a market against the top

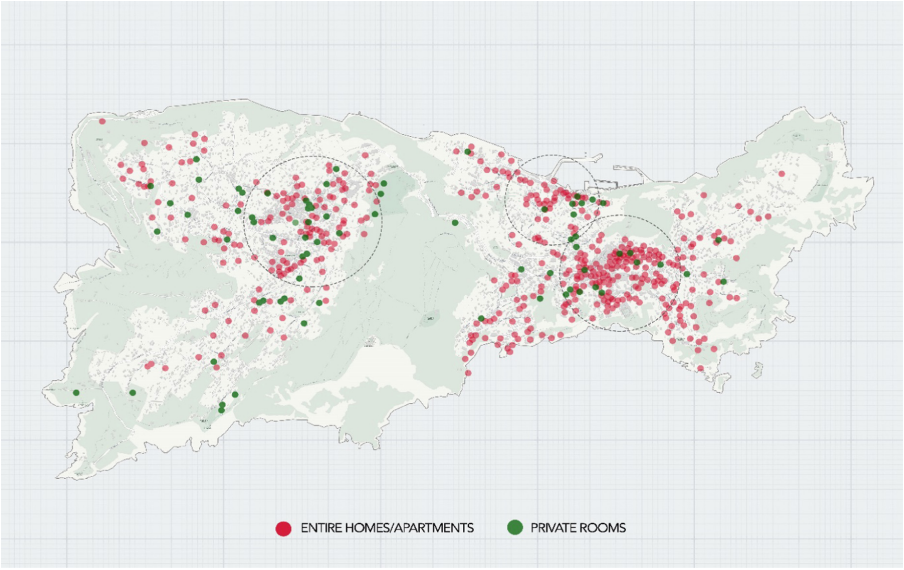

Fig. 5. Supply distribution in Capri e Anacapri

Airbnb cities in the world. These are markets with high numbers of listings and extensive historical data. Market Grade is calculated by comparing the performance of a market against the top 2,000 Airbnb markets globally.

The grade is determined by the percentile in which the market sits on the basis of five key metrics:

Rental demand shows how often rentals are booked throughout the year and the relative travel demand in this market by using a combination of annual occupancy and listing growth rates (high score = high travel demand);
Revenue growth is a metric used to understand if vacation rental listings in this location are earning more this month than they did in the same month last year. This score is calculated by looking at the change in year-over-year RevPAR (revenue per available room) for properties that received bookings in both time periods.
Seasonality indicates the difference in demand for travel in this market between peak and low seasons. This score is calculated by finding the percentage difference between the minimum and maximum monthly average revenue of the past year.
Regulation is a score attributed to host and property behaviours to understand whether they are consistent with Airbnb's policy. While some cities heavily restrict or outright ban certain short-term rentals, others have implemented permitting processes or capped the total number of units allowed. Although some may avoid purchasing in areas with complicated or heavy regulation, savvy investors often know how to navigate the various requirements within markets that offer great investment opportunities.

Investability: this score compares the cost of homes in the area to the average short-term rental income of full-time rental properties, indicating whether homes in this market are a good investment.

On the reference scale of the Market Grade that ranges from A (best grade) to E (worst grade) both Capri and Anacapri are B +. Seasonality, of all data, is the starting point for a precise analysis of Anacapri and the Capri Island in general. Their low score is clearly justified by the analysis of demand shown in Figs. 6 and 7.

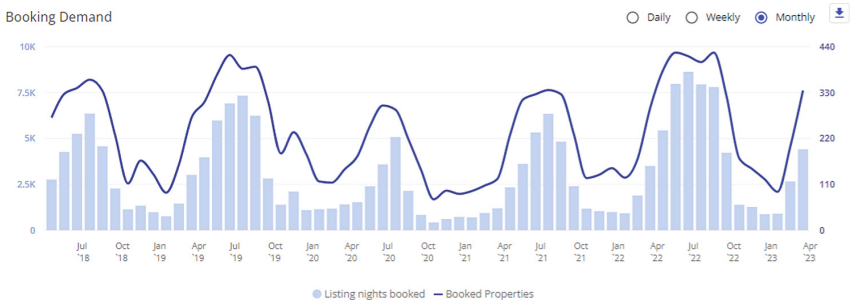

Fig. 6. Booking demand in Capri

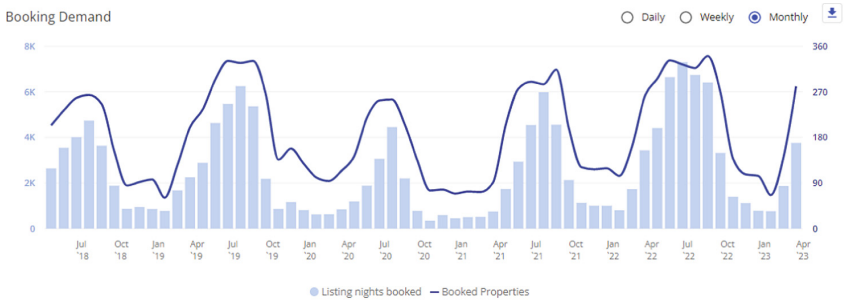

Fig. 7. Booking demand in Anacapri

As a location renowned for its distinctive landscape and lifestyle, particularly during the summer season, it is unsurprising that the highest number of visitors are recorded between June and August. Despite 2019 being an exceptional year for the Island's tourism industry, with record numbers of visitors, it was matched in 2021 and surpassed in 2022.

The peaks of demand were recorded in June 2022 in Capri, with a number of 7,977 nights booked (an increase of 15.47% compared to July 2019, where the number of nights booked was 6,908) and in July 2022 in Anacapri, with a number of 7,303 (an increase of 16.83% compared to 6,251 in August 2019). The fluctuating trend in the supply of dwellings by owners corresponds to a non-constant and sinusoidal trend in demand. This is true for both municipalities: property owners tend to make their properties available mainly in the third quarter of the year, the summer quarter, with a marked decrease in the

first quarter of the year. However, the second quarter of 2020 saw the lowest availability of listings, evidently due to the impact of the Covid-19 pandemic. Nevertheless, the relatively large gap between active supply in different quarters of the year has decreased in 2022. These data show that changes are taking place, and Capri may be moving towards year-round tourism rather than being mainly attractive in the summer.

This is confirmed by AirDNA's analysis of rental activity. The platform segments all active properties according to the number of days they are available for rent and actually rented in the last year. In fact, AirDNA is able to distinguish between blocked days and booked days, which is otherwise unavailable because booking platforms hide this information from the public. AirDNA can intercept whether a booking has actually been made or whether the host has blocked the calendar. They are classified as "full-time" rentals if they have been available for at least 181 days in the last year. In 2021, only 13% of dwellings were available for rent between 181 and 365 days a year, given the seasonality of tourist activity on the Island. However, by March 2023, the percentage had risen to 31%.

4.2 Comparison Between AirBnb and "Traditional Rentals"

In recent years, as shown in previous analyses, there has indeed been a steady development of the platform. Therefore, it is interesting to understand whether, and to what extent, the Airbnb phenomenon is more economically advantageous than a traditional rental.

The year-on-year increase in the share of dwellings used for this innovative business implies a withdrawal from the traditional housing market, and this has important implications for the latter. Figures 8 and 9 show Airbnb's total revenue by type of advertisement over the years.

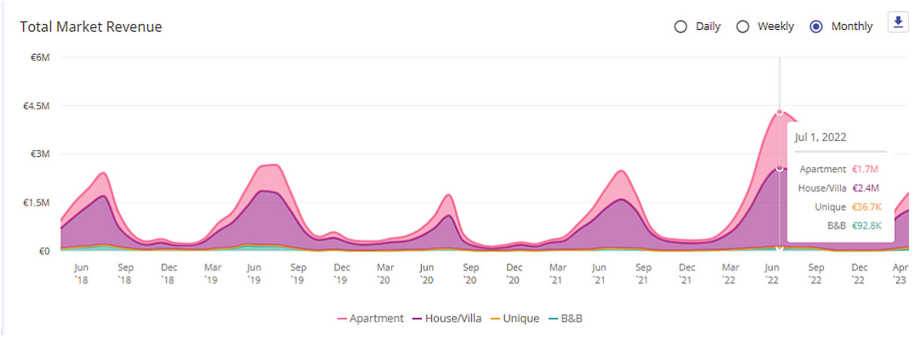

Fig. 8. Monthly Total Market Revenue in Capri

The volume of business generated by Airbnb is clearly significant. The highest revenues recorded so far were generated in both Capri and Anacapri in July 2022, with differences. In Capri, to a greater extent, and in Anacapri, to a lesser extent, the type of property that generates the most revenue is villas. This testifies to the Island's configuration, which, thanks to its historical fame, is known as a place where luxury

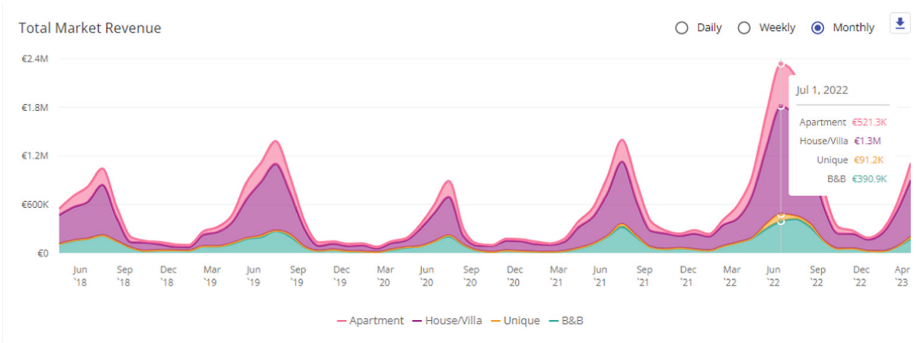

Fig. 9. Monthly Total Market Revenue of Anacapri

and exclusivity prevail. Apartments and B&Bs are the next most profitable property types. However, it is evident that the revenues generated by Airbnb in the municipality of Capri are much more stable, sometimes even doubling or tripling those recorded in Anacapri, except for the B&B category, which is more profitable in Anacapri (as mentioned earlier) and has been impacted by mass tourism later than Capri. In any case, these are extremely significant incomes. Comparing these revenues with those plausibly derived from a "traditional" rental would reveal that the latter does not yield as much as a short-term rental. AirDNA's Renting section can provide information on the annual earnings that can be obtained by renting a property. Figures 10 and 11 show, respectively, the annual revenue from a property in Capri and Anacapri rented by Airbnb (considering an average property of two bedrooms and two bathrooms).



Fig. 10. Annual revenue from a property in Capri

The annual gain expresses the estimated income that this property would earn as a short-term rental over the next year. The potential profit by making the property available next year is €73,700.00 for Capri and €54,100.00 for Anacapri (-26.59%).

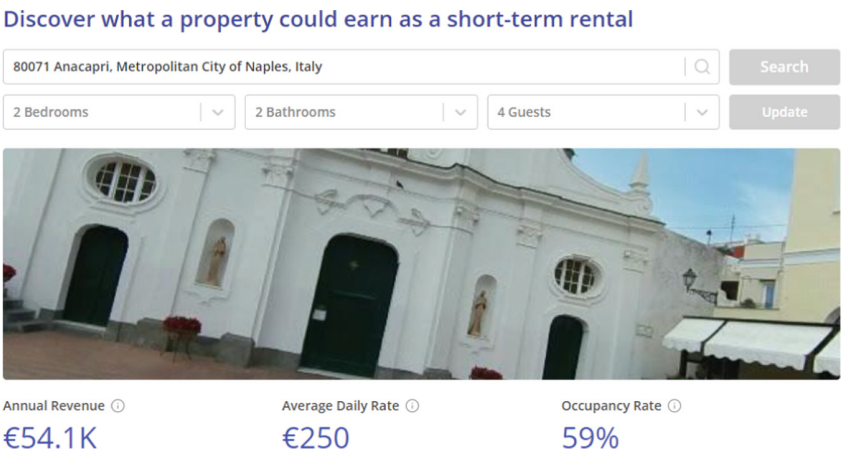

Fig. 11. Annual revenue from a property in Anacapri

The average daily rate is the estimated average nightly rate for all bookings made in the coming year. The occupancy rate is the estimated percentage of days that this property will be booked over the next year. A traditional rental, where the property is occupied for at least a full year, does not yield as much income as a short-term rental for a few months of summer activity. To demonstrate this, AirDNA's Renting section enables to calculate the potential earnings of a property from short-term rentals.

One of the first consequences is that house prices have risen beyond the reach of most residents, who are faced with a market that is much higher than the official quotations published by the Borsino Immobiliare: for houses in the central area and in the first band, for example, those above the average for the area, the quotation updated in April 2023 indicates a maximum value of €25.14/m^2 in Capri and €19.75/m^2 in Anacapri. However, an analysis of the evolution of the prices of residential rental properties reported by some online agencies, such as Immobiliare.it, shows that in the last two years, the average price in the municipality of Capri reached its peak in July 2022, with a value of €31.60/m^2 (+26.89% compared to the listing value), while Anacapri reached its peak in February 2022, with a value of €26.21/m^2 (+32.71% compared to the listing value).

4.3 On the Road to Sustainable Tourism

The tourism sector contributes to the creation of value and jobs but, if it is not well managed, it risks becoming damaging to local communities and places themselves.

If it is true that the tourism sector generates employment, we must constantly question the nature of this work, which in Italy, and especially on Capri Island, is seasonal, occasional, with temporary contracts, and on the impact that tourism has on the lives of the inhabitants of the places visited.

Another critical aspect is related to touristification. Touristification means that a city has to satisfy the needs of tourists and not those of its inhabitants. At the center is the consumption and wear and tear of the city itself: its life, that of its inhabitants, its heritage, and its history are consumed, in the "take-make-dispose" logic typical of the linear

economy. In the wake of Covid-19, the collapse of tourism has offered the opportunity to recognize the limits of an unsustainable and harmful growth model and to modify the imbalances created by overtourism [18]. Overtourism is not only a consequence of private interests at stake but also of a strategy of urban growth by public administrations that promote tourism growth while also complaining about its effects. On Capri, the "after" was paradoxically worse than the "before". This contradiction is the result of an unsustainable growth model.

According to the World Tourism Organisation (WTO), the responsible tourism is a form of tourism that supports the traveller and the territory by creating opportunities for the future [19]. Sustainable tourism is a broad term used to describe responsible travel practices that, among other things, respect the environment; do not exploit an area, a culture or a population; have an ethical and virtuous purpose; be economically sustainable for the host population; and have a socio-cultural interest, meaning that the whole trip is in the interest of the host population as well as respecting it [20].

Starting from a healthy regulation that does not limit but optimises the possibilities offered by the platform, and that aims at a strategy of valorisation of the territory and a truly sustainable tourism [21], and to recover something of the rhetorical perspective of solidarity that was the basis of the sharing economy/home sharing, it is necessary for hosts to undertake sustainable initiatives for the tourists they receive [22, 23]. These may concern, for example: experiences of personalised visits to the few truly typical Capri houses left, the possibility of interacting with the locals, getting to know their daily routines, provide "classes" in local cuisine, "sponsor" hidden routes to enjoy the truest views and to venture into the rocky nature of the Island, experiencing its authenticity in a conscious, sustainable and enriching way.

In this perspective, a new platform, called "Inside Capri" (https://alessandrastaiano9.wixsite.com/website) is here proposed aimed at the valorization of local cultural heritage and the cooperation among tourists and the community, that is to make the tourism sector more sustainable.

The platform was developed to propose an alternative program for communicating and informing about Capri Island. The platform is based on a logic of sharing and collaboration, in line with the circular economy principles. It has characterized by dynamism. In fact, everyone has the opportunity to integrate it by inserting posts, contributing also to increase the knowledge linked to certain "hidden" places on Capri Island.

As you scroll down the page, a first section aims to propose experiences that are related not only to learning about the area, but also to learning about the local culture and history. It provides information for local cooking classes, excursions, unconventional tours, and immersive experiences with local guides (Fig. 12).

Furthermore, through Inside Capri, an unconventional map (Fig. 13) can be consulted to promote a wider knowledge of the area, showing the most intrinsic and significant places on the Island. In fact, some of the territory's most important "places of value" are shown: by framing the QR code, you can access websites with detailed descriptions of these places, which are usually invisible to visitors. The map can be downloaded from the platform at any time.

Finally, there is a section dedicated to Capri's most important personalities and traditional events. This last section can be expanded and enriched by anyone, according

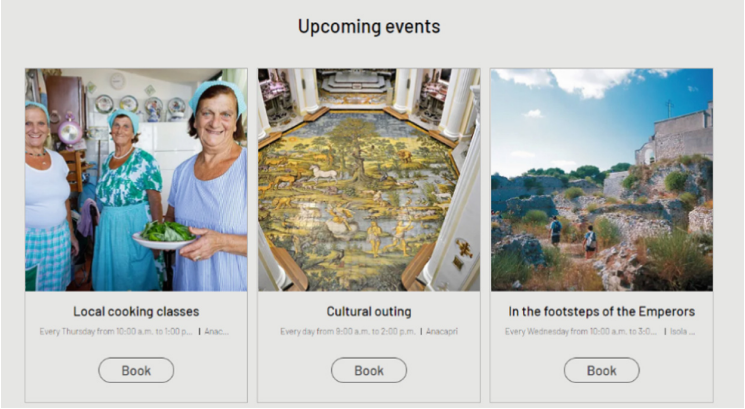

Fig. 12. Screenshot of Upcoming events section

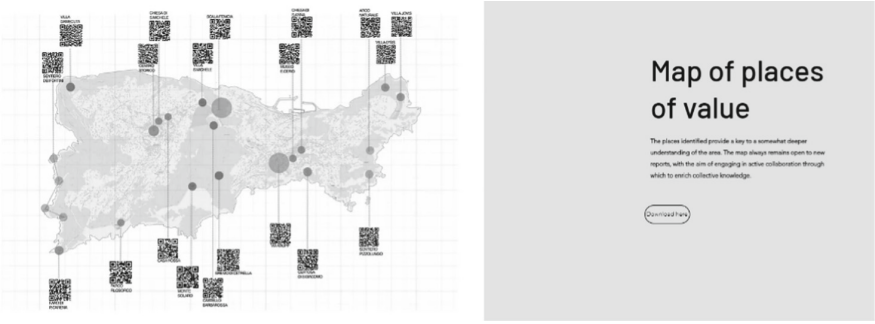

Fig. 13. Screenshot of map "Places of value"

to a logic of sharing: experiences lived or handed down by others, stories, anecdotes can be told to generate a collective enrichment of the place.

5 Conclusions

The development of Airbnb in Italy and Capri influences and affects the traditional rental market, as the above analyses showed.

It turns out that Airbnb's activity tends to deviate from the sharing economy model it claims to follow. In fact, most hosts are commercial operators with multiple accommodation units that are fully available to tourists throughout the year, or at least to those who earn the most from the platform. Indeed, where the proportion of timeshare hosts is highest and the proportion of whole apartments offered on the platform is predominant compared to single or shared rooms, the impact of Airbnb as a driver of gentrification has been found to be strongest [24].

Thus, the short-term rental market, where Airbnb is active, eventually displaces the long-term housing market, significantly reducing the housing stock and increasing house prices and rents.

It has been observed that Airbnb listings tend to be concentrated in historic centers, gentrified neighborhoods, and adjacent areas, and not (as the platform claims) in suburban areas that are typically excluded from tourist traffic.

As housing becomes increasingly the only form of economic security, Airbnb is acting as a social divider by preventing homeless people who want to rent from accessing housing.

In addition, it can be argued that due to the gentrification of tourism and the massive flow of visitors made possible by the spread of Airbnb, cities are losing their soul and their distinctive features [25]. The tourism industry displaces residents and consumes heritage without creating a fair distribution of income, but rather by exacerbating social inequalities [26].

In the absence of forward-thinking government policies, or in a context such as the current one where the state instead wants to promote tourism at all costs, it is necessary to hold the tourist accountable as much as the citizen [27]. The conscious tourist is the one whose right to enjoy the urban space does not interfere with the right of the inhabitants to enjoy it; likewise, the conscious citizen is the one who, aware of his rights, claims his right to space. Houses should be used for living in rather than staying in, and cities should be places for living in rather than merely visiting [28].

The Inside Capri platform aims to develop a progressive construction of the territory's history [29], which helps to understand its unique characteristics and enables each inhabitant to share their story and life experiences, in order to make tourists see the territorial resources in a different light. Similarly, tourists can share their own stories through interactions with locals [30]. This type of intercultural exchange can lead to mutual enrichment in a human sustainable perspective.

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Author Contributions. Conceptualization, M.C., F.N., G.P.; methodology, M.C., F.N., G.P.; validation, M.C., F.N., G.P.; formal analysis, A.S.; investigation, A.S.; writing-original draft preparation, A.S.; writing-review and editing, A.S., F.N., G.P.; visualization, A.S.; supervision, M.C. All authors have read and agreed to the published version of the manuscript.

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The One-Stop Shop Business Model for Improving Building Energy Efficiency: Analysis and Applications

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Abstract. Due to the significant contribution of the building stock to total greenhouse gas emissions, policies and measures have been focused on efficiency improvement and renovation works of old and outdated buildings. Those measures are often shaped as subsidies, tax rebates, and other economic incentives for the building owner. In turn, that has stimulated the rise and development of innovative business models meant to exploit the opportunities offered by incentive policies. This research aims to analyze the "One-stop shop" business model, which is among the most used in building redevelopment. It is based on the assumption that the customer interfaces with a single contractor, usually an Energy Service Company, which takes care entirely of the efficiency improvement works, acting as the proponent and guarantor of all the interventions. Here, the "One-stop shop" business model's primary features are derived through a case study analysis focused on refurbishment projects carried out in Germany, France, Spain, Belgium, and the Netherlands. The case studies are analyzed using the Rough Set approach. By identifying meaningful, well-defined clusters and sometimes vague and fuzzy subsets of the case studies, the significant relationships among their characteristics are highlighted. Major results are as follows. Concerning the business models, Energy Service Companies are not overrepresented, while construction firms are important players, too. Furthermore, incentive measures are used in nearly half the case studies, especially in France. Concerning the renovation works, they mostly feature replacing the heating system, adding insulation layers to the building envelope, and installing a mechanical extract ventilation system.

Keywords: Business models · Energy Service Company · Construction industry · Real estate market · Energy efficiency

1 Introduction and Background Literature

Starting from the seventies, energy saving first and energy efficiency later have been among the main concerns of several western nations [1, 2]. Energy performance improvement has been pursued - using a variety of policies - in several sectors, with the building industry holding a prominent place [3]. Concerning the construction industry and

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the real estate market of the European Union (EU) countries, Directives 2002/91/EC, 2010/31/EU, and 2018/844/EU set the framework for the national policies and measures, which include mandatory standards, subsidies, tax rebates, as well as other cash and in-kind incentives [4, 5].

In turn, the wide range of incentive policies and measures put in place so far by EU member countries has stimulated the rise and development of innovative and tailored business models (BMs) [6–10], which are seen as essential for promoting the circular economy in the building industry and pursuing the long-term sustainability goals [11, 12]. According to the literature, the BMs meant to attain building energy efficiency - and to exploit the related public incentives - differ for the players involved, the relationships they establish, and the link to an energy certification system or not. More to the point, some BMs feature an individual contractor responsible for all the energy efficiency improvement works while, in other BMs, the customers interface with two contractors or more [11, 13]. In addition, the relationships established between customers and contractors can be modeled according to different settings, such as energy performance contracting (EPC) [14], energy service contracting (ESC) [15], and integrated energy contracting (IEC). The agreed contract further implies different allocations of costs and energy savings among the involved parties [16–19]. Lastly, the BMs may or may not be directly linked to a mandatory or voluntary energy certification system, such as EPCs [20, 21], LEED, and BREEAM [22–24].

One of the most used BMs in the construction industry is the so-called "One-Stop Shop" (OSS) business model [25] (Fig. 1). It is characterized by the involvement of an individual contractor, which is typically an Energy Service Company (ESCo) [26–30]. The contractor is responsible for the project's quality and outcomes; it bears the upfront costs and performs the efficiency improvement works. Side players in the OSS BM are energy consultants and market facilitators, assisting the customers in the financial closing of the energy refurbishment projects.

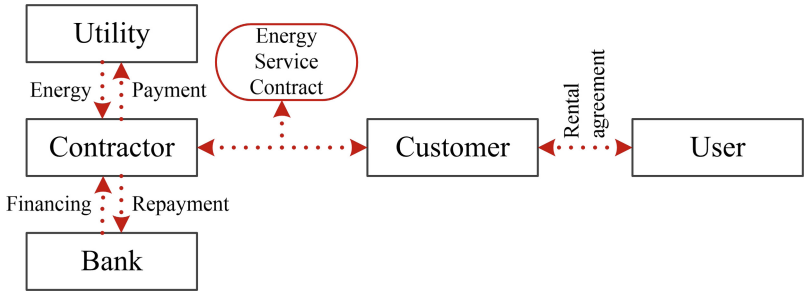


Fig. 1. Players and relationships in the One-Stop Shop business model.

The literature has identified four sub-model concepts related to the OSS BM, though implemented with mixed success; they are as follows: Dong-CleanTech, ProjektLavenergi, ENRA, and ENRENOV [31]. The first - Dong-CleanTech - has been used in Denmark to improve the energy performance of buildings dating back to the seventies, mainly by using cladding insulation, installing heat pumps and solar panels, and replacing frames

and windows. Likewise, the second sub-model concept - ProjektLavenergi - has been used in Denmark, especially for refurbishing single-family houses built between the seventies and the eighties; the efficiency works mainly concern the heating systems. The third - ENRA - has been developed in Finland to renovate residential properties, especially by improving insulation and windows.

A recent search for innovative business models in the building industry specially meant to carry out efficiency-related works has led to the identification of about fifty case studies across Germany, France, Spain, Belgium, and the Netherlands. Of them, fourteen cases fall within the framework of the OSS BM. This study aims to provide an overview of their distinctive features. In particular, we are interested in recognizing and determining the commonalities among the case studies as well as their differentiation factors concerning both the BM's arrangement and the efficiency works carried out on the properties.

The following section describes the data processing method. Section 3 introduces the case studies and the data gathering process. Section 4 is devoted to the presentation and discussion of the results. The last section draws the conclusions.

2 Method

Given the goal of identifying the commonalities and the differentiation factors of the projects carried out under the framework of the OSS BM, data is processed using the Rough Set analysis. The Rough Set theory was introduced and developed by the Polish mathematician Z. Pawlak [32]. The rationale behind the approach [33] makes it suitable for dealing with incomplete and imprecise information systems [34–36], as well as for multi-criteria decision aid [37–42].

This analytical tool allows us to identify the relationships between the attributes we use to describe the OSS BM and then cluster the case studies into sets described by a selection of significant features. The boundaries of those sets are sometimes well-defined, while other times somewhat vague. Several case studies are clustered together into a given group because they share all the attributes defining that set; instead, other case studies only partially belong to a set since some - but not all - of its features characterize them. In other words, a boundary region is assumed to surround each distinguishable set of the analyzed objects. The objects falling in that boundary region possibly, but not certainly, belong to the group due to the occurrence of somewhat vague, imprecise, and ambiguous relationships [43–48].

The Rough Set approach's various applications include the study of urban renewal projects [49, 50] and building energy efficiency measures [51, 52]. The analysis below is performed using the package ROSE2[1], a software developed by the Laboratory of Intelligent Decision Support Systems at the Poznań University of Technology [53, 54].

3 Case Studies

The case study list has been identified by consulting reports of EU-funded projects and fact sheets of public monitors on the energy refurbishment of outdated buildings across Central Europe. Several cases are located in France and Belgium, especially in

[1] See https://fcds.cs.put.poznan.pl/IDSS/software/rose.htm, last accessed 19.02.2023.

the capital cities, only a couple in the Netherlands, and just one in Germany and Spain (Fig. 2). Most cases involve outdated housing. However, there are a few commercial buildings, provided the arrangement of the relationships among the parties involved in the renovation works can be related to the OSS BM.

Data collection focuses on three domains (Table 1): the distinctive features of the business model, the characteristics of the real estate asset to be refurbished, and the kind of efficiency-related works. Concerning the business model, we consider the public or private nature of the property owner (distinguishing among publicly-owned and semi-public organizations, private non-profit companies, and private for-profit companies), the financial promoter, the upfront cost - namely, the invested capital - and the use of subsidies and tax incentives.

As far as the property features are concerned, the following data is considered: construction year, building typology, construction materials, floor area, energy rating band before and after the efficiency project is carried out, and energy performance index (EPI) before and after the efficiency measures are taken up. Furthermore, regarding the kind of efficiency improvement works carried out, the adopted measures are listed according to the following categories: insulation and cladding system (the latter including windows and frames), heating and cooling system, photovoltaic and solar thermal system, mechanical extract ventilation system, and rainwater harvesting system.

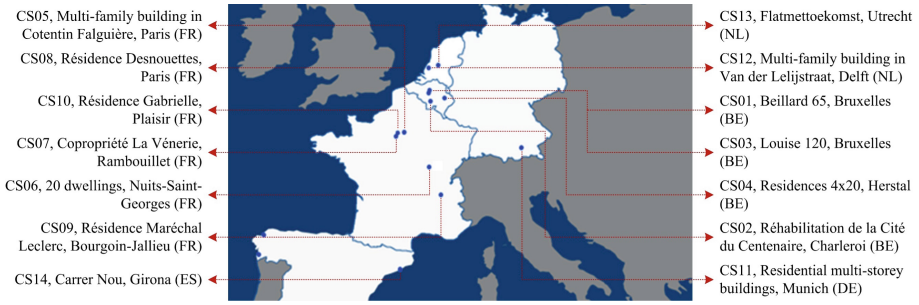


Fig. 2. The fourteen case studies and their location.

Two-page summary sheets have been prepared for each case study. An excerpt from them can be found below (Figs. 3–4). The first page recaps information about the property's characteristics, such as location, ownership, size, building typology, construction year, energy rating band, and the energy performance index before and after the renovation works. A summary of the efficiency improvement measures and a more detailed description of them is also included. On the other hand, the second page focuses on the information relating to the adopted business model with a characterization of the financial promoter and the building owner, besides a diagram representing the relationships among the players.

Table 1. The variables and the coding system.

Domain	Variable	Code	Categories
Business model	Ownership	OW	1: publicly-owned and semi-public organization; 2: private non-profit company; 3: private for-profit company
	Financial promoter	FP	1: ESCo; 2: construction company; 3: architecture firm
	Incentive measures	IM	(binary) 1: use of subsidies or tax rebates
	Upfront cost	UC	1: $\leq$ 2mln Euros; 2: $\leq$ 4mln Euros; 3: $\leq$ 8mln Euros
Real estate asset	Size (net floor area)	SZ	1: $\leq$ 3,000 m2; 2: $\leq$ 10,000 m2; 3: $\leq$ 22,000 m2
	Construction year	CY	1: 1950–1965; 2: 1970–1980; 3: 1990–2010
	Building typology	BT	1: condo; 2: terraced house; 3: other
	Construction material	CM	1: reinforced concrete; 2: steel; 3: bricks
	Rating band (ante)	RBa	1: D; 2: E; 3: F; 4: G
	Rating band (post)	RBp	1: A; 2: B; 3: C; 4: D
	EPI (ante)	PIa	1: 160–199 kWh/m2 y; 2: 200–229; 3: 230–299; 4: 300–399; 5: higher than 400
	EPI (post)	PIp	1: 20–39 kWh/m2 y; 2: 40–64; 3: 65–89; 4: 90–149; 5: 150–200
Efficiency-related works	Insulation	INS	(binary) 1: renovation works include measures on the element or system
	Cladding (including windows and frames)	CLA	(binary) 1: renovation works include measures on the element or system
	Ventilation	MEV	(binary) 1: renovation works include measures on the element or system
	Cooling	COO	(binary) 1: renovation works include measures on the element or system

(*continued*)

Table 1. (*continued*)

Domain	Variable	Code	Categories
	Heating	HEA	(binary) 1: renovation works include measures on the element or system
	Photovoltaic	PVS	(binary) 1: renovation works include measures on the element or system
	Solar thermal	STS	(binary) 1: renovation works include measures on the element or system
	Rainwater harvesting	RHS	(binary) 1: renovation works include measures on the element or system

4 Results and Discussion

Using the first variable describing the BM - namely, ownership - as a discriminating factor leads to identifying three primary, well-defined clusters mirroring the categories of the variable itself (Fig. 5).

The first group includes five publicly-owned real estate assets; four are condos relying on construction companies for renovation work, which always involves adding insulation layers to the building envelope and often includes replacing the heating system. Notably, only one case study features the intervention of an ESCo as the financial promoter of the transaction and the interface between the involved parties.

The second set features only three case studies where a private non-profit company owns old, middle-sized properties; again, the refurbishment is essentially pursued by adding insulating layers to the buildings. Two of the properties are reinforced concrete condos facing high upfront costs in the range of 4 to 8 million Euros. Two cases feature the involvement of an ESCo. The property assets owned by private for-profit companies belong to the third cluster, which includes two subsets: on the one hand, four reinforced concrete buildings renovated as far as the cladding system is concerned; on the other hand, two relatively recent nonresidential buildings.

The information provided by the above three sets is relatively scarce and scattered. The description of the case studies and the relationships among the analyzed variables improves when considering - sometimes vague and fuzzy - subsets. Pertinent examples are the layered subsets in the first group (Fig. 6). It turns out that reinforced concrete is the most common construction material for those case studies, and properties predominantly have an average size between 3,000 and 10,000 square meters. Furthermore, renovation often involves installing a mechanical extract ventilation system besides replacing the heating system and adding insulation layers to the building envelope.

CASE STUDY N°01

Belliard 65

BUILDING INFORMATION

Location: Bruxelles
Ownership: private
Net floor area: 5134 m2
Building typology: 11 floors building (3 of them underground) with concrete pillars
Construction year: 1990's
Intervention typology: Extension

EPC before energy measures: /
EPI before energy measures: /

EPC after energy measures: B
EPI after energy measures: 83,00 kWh/m2 yr

Energy measures:
- Heating system + production od domestic hot water
- Cooling system
- Ventilation system
- Lighting system
- Renewable sources

Description of the efficiency improvement measures:

- Heating system
- Heat production (heating) via two HR condensing gas boilers and production of local domestic hot water via air/water heat pump.

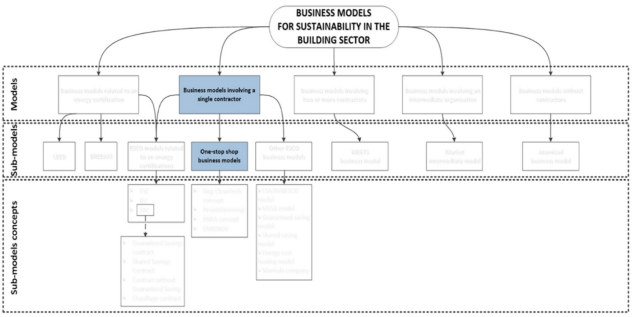
- Cooling system
- Cold production by two high performance refrigerating machines with freechilling.
- Emission of hot and cold via reversible hot and cold radiant metal ceilings with access to the thermal mass.

- Ventilation system
- "Oversizing" of the ventilation system (double-flow mechanical ventilation with plate heat exchanger and by-pass) .

- Lighting system
- Presence-motion detectors that control the switching on and off of the lights.
- Installation of high efficiency LED type luminaire and luminaire luminous flux adjustment through twilight sensors.

- Renewable sources
- Photovoltaic installation ensuring a production of 65,000 kWh/year.

Fig. 3. Excerpt from the summary sheets of the case studies: CS01.



BUSINESS MODEL: One-stop shop

Financial promoter: Herpain Entreprise
Building owner: AXA REIM Belgium

Relationships among business model subjects:

- **Herpain Enterprise** is the main contractor of the project and thanks to the collaboration with others actors like Matriciel sa (thermal consultant agency), Pirnay Engineering (structure calcolist), B4F (certification agency), François De Bloudts (assistance to the Contracting Authority Advisers), Tom Vandervorst (structure calcolist), Company SPIE (company in charge of HVAC and sanitary batches), Company ITB (company in charge of the elevator lot), Company Nizet (company in charge of photovoltaic panels and high voltage booths) is able to realise the measure of efficiency. It provides AXA REIM Belgium with all the information and types of services required and frees the customer from any responsibility.
- **AXA REIM Belgium** is the customer and it's a management company that invest in energy long savings. As foreseen in the One-stop shop BM, it is responsible for repaying the Herpain Enterprise for the works performed after they are completed.

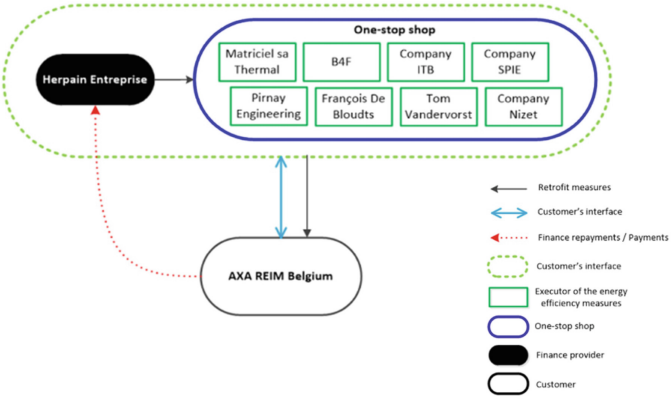


Fig. 3. (*continued*)

CASE STUDY N°07

Copropriété La Vénerie - Rambouillet

BUILDING INFORMATION

Location: Rambouillet
Ownership: private
Net floor area: 13350 m2
Building typology: collective housing of 148 flats and 5 commercial locals
Construction year: 1977
Intervention typology: renovation

EPC before energy measures: D
EPI before energy measures: 169,00 kWh/m2 yr

EPC after energy measures: B
EPI after energy measures: 90,00 kWh/m2 yr

Energy measures:
- Building's envelope
- Ventilation system
- Lighting system

Description of the efficiency improvement measures:

- Building's envelope

- Renovation with thermal insulation from the outside of the 7 buildings of the residence
- Insulation of attic floors and demossing of the roof
- Insulation of lower floors facing the outside
- Replacement of shutters
- Replacement of the original private and collective carpentry

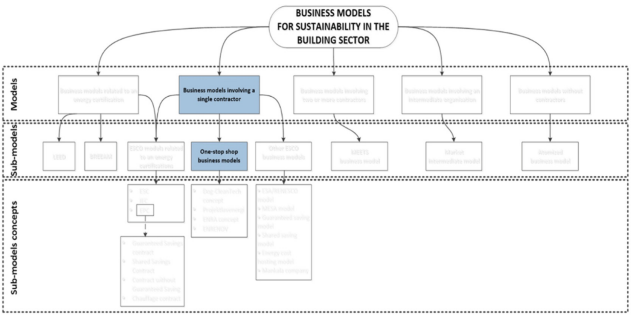
- Ventilation system

- Condemnation or adaptation of refuse chutes
- Improved radiators
- Installation of heating cost allocators
- Improved intercoms

- Lighting system

- Improved lighting in common areas

Fig. 4. Excerpt from the summary sheets of the case studies: CS07.



BUSINESS MODEL: One-stop shop

Financial promoter: Ile de France energie
Building owner: Private owners of the flats

Relationships among business model subjects:

- **Ile de France energie** is the main contractor of the project. Thanks to the collaboration with other companies such as SEEF (energy company), ZA consulting (engineering company) and Cidelec it is responsable for the efficiency measures and for the energy contract.
- **The private owners of the flats** decided to carry out the efficiency works in order not to see the value of their properties depreciated since the neighboring condominiums had had efficiency works. They promote energy efficiency measures and are responsible for repaying Ile de France energie for the works performed. They are not responsable for the execution of efficiency measures.

Use of government's funding or tax incentives:

- 1 030 000 € state aids:
- CEE : 110 800 €
- Region : 200 000 €
- CITE (Crédit d'impôt): 125 000 €
- Anah, Commune, Département des Yvelines total : 590 103 €

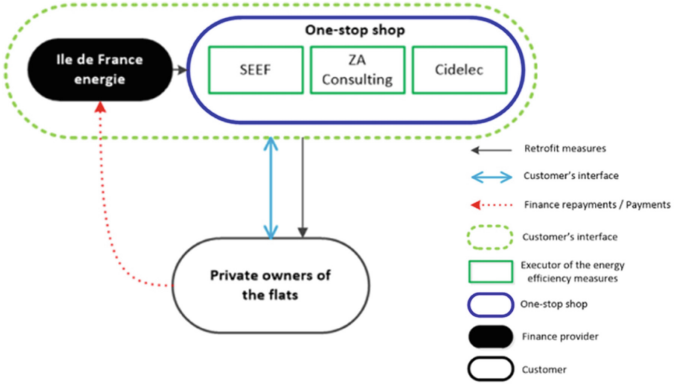


Fig. 4. (*continued*)

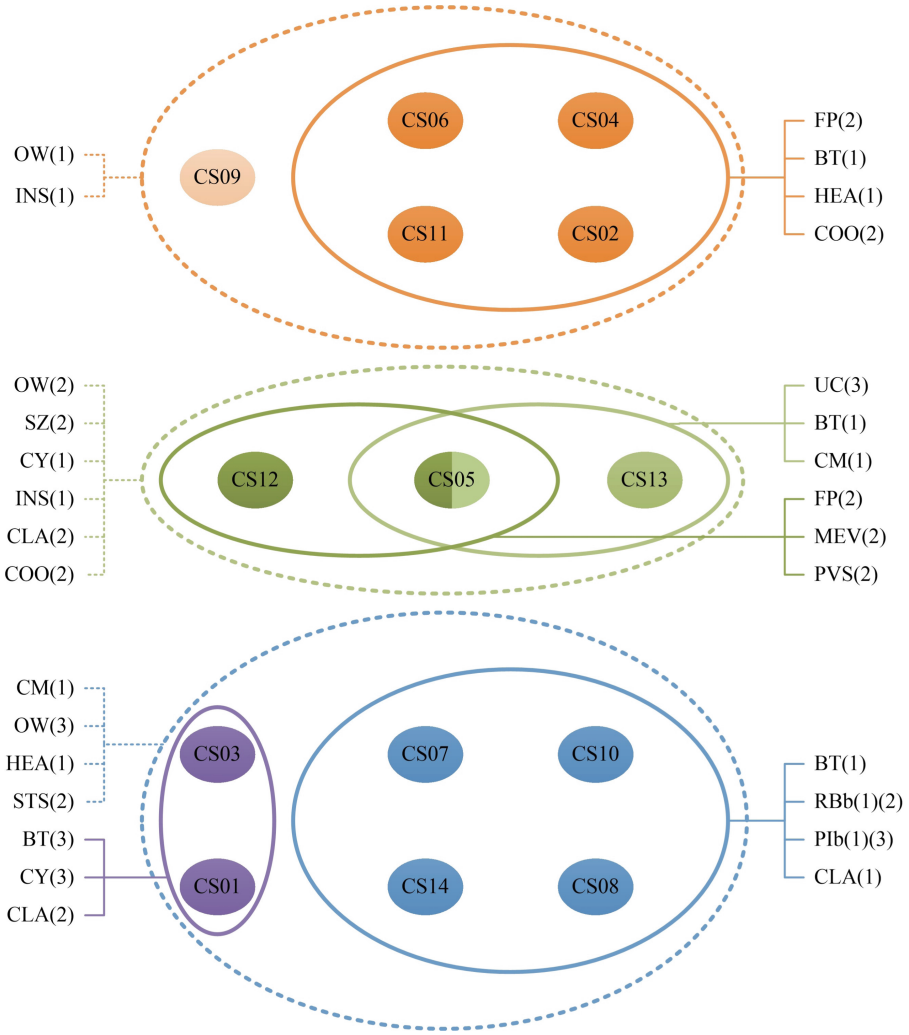


Fig. 5. Main clusters of the case studies.

A further detailed view of the case studies and the relationships among the analyzed domains and variables is offered by the consideration of additional subsets in the first cluster (Fig. 7). The involved real estate assets are essentially outdated, having been built in part between 1950 and 1965 and partly during the seventies. Despite the physical obsolescence due to age, the refurbishment works led to an overall acceptable energy performance for three of them: the rating band after the renovation is B, with the EPI in the range of 65–89 kWh/m2 y. The result is even better for the remaining two case studies, which are now A-rated. Finally, there is little to add regarding efficiency-related works, except for using photovoltaic panels in just two cases. Incentive measures are also used in two cases; we will get back to that later.

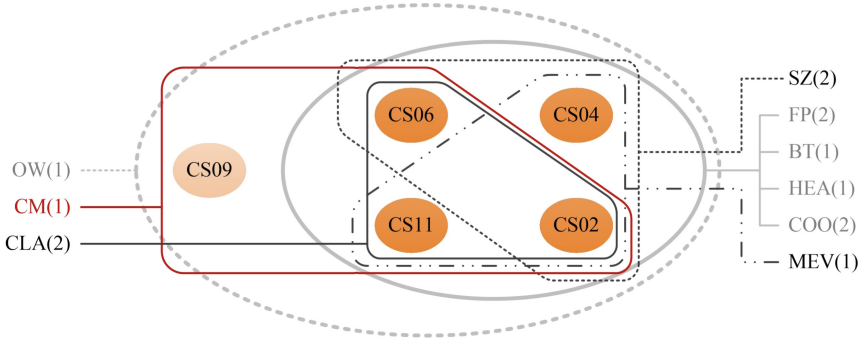


Fig. 6. Layered subsets in the first cluster of the case studies.

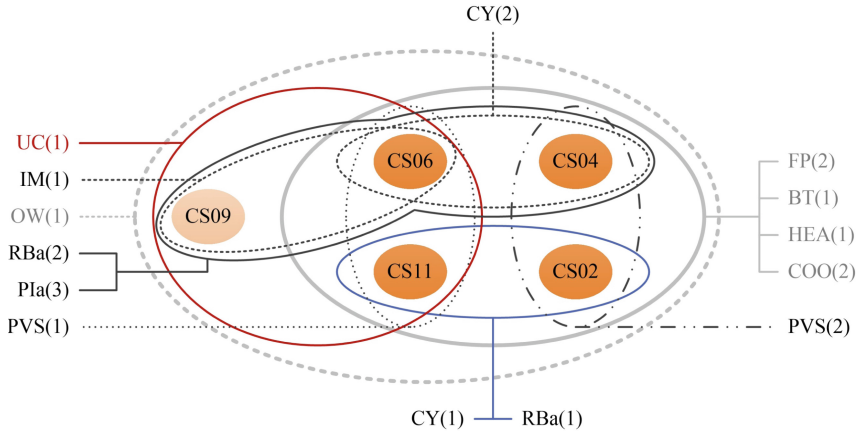


Fig. 7. Additional subsets in the first cluster of the case studies.

Several subsets that intersect each other also characterize the third cluster (Fig. 8). The subset that includes three French case studies - CS07, CS08, and CS10 - is quite interesting due to two characteristics: the largest properties in the sample with a size up to 22,000 square meters and the use of incentive measures to support the investment. In fact, the use of those measures is a distinctive feature of the French case studies (Table 2).

Additional specific subsets that cluster the case studies in pairs can be found for the third group (Fig. 9). Although each represents a fraction of the whole dataset, their joint reading is helpful to deepen the interpretation and expand the knowledge of the OSS BM. A couple of case studies feature an ESCo as the financial promoter, and incentive measures are used in both cases. Instead, incentives are usually not exploited when construction firms act as financial promoters.

The empirical evidence above suggests revising the hypothesis put forward in the introduction of this paper. The OSS BM is not intrinsically dependent on the measures meant to incentivize building energy efficiency, at least not as much as one of the OSS BM players, especially the ESCo.

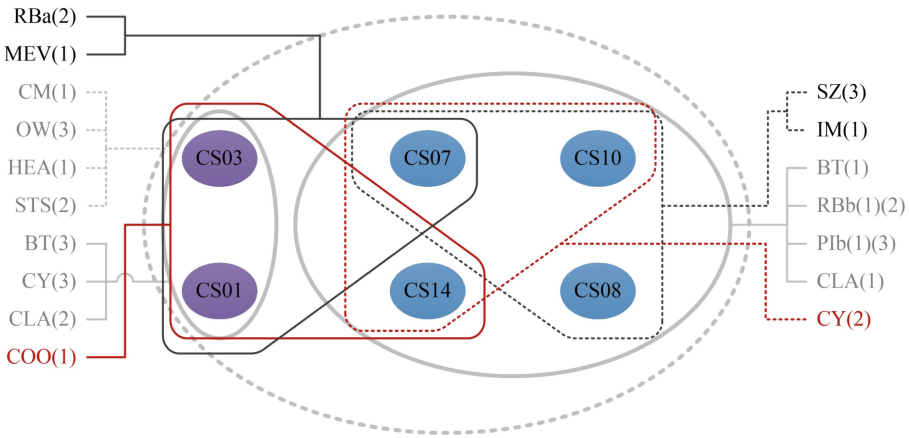


Fig. 8. Layered subsets in the third cluster of the case studies.

Table 2. Sources for the incentive measures adopted in the French case studies

Organization	Description
ADEME	The French ecological transition agency is responsible for evaluating and financing innovations that can help reduce energy consumption and greenhouse gas emissions This funding source was used in CS06 and CS09; the latter was selected in two calls for regional projects by ADEME and the Rhône-Alpes region and benefited from grants covering 26% of investment costs
ANAH	The French national agency for housing improvement subsidizes home comfort enhancement. Subsidies vary between 25% and 50% of the investment depending on renovation work and rent This funding source was used in CS07 and CS10
banks	Eco-PTZ is an interest-free loan that can be used by the owner-occupant or lessor of a dwelling to finance energy renovation work up to 50,000 Euros The case studies CS08 and CS10 benefited from this financial support

Furthermore, the third cluster shows interesting findings concerning building energy performance before and after the completion of renovation work. Several case studies in this group involve mid-tier buildings as far as energy performance is concerned. Their rating bands were D or E before the refurbishment. Nevertheless, none of them makes the shift to the A rating band after the refurbishment is carried out; some are B-rated, others C and even D. The outcome seems to be unrelated to the amount of the investment. Instead, it appears to be the consequence of the combination of constraints due to building age and kind of efficiency-related works primarily focused on the envelope and heating, with much less attention paid to other systems, such as mechanical extract ventilation, cooling, and photovoltaic or solar thermal.

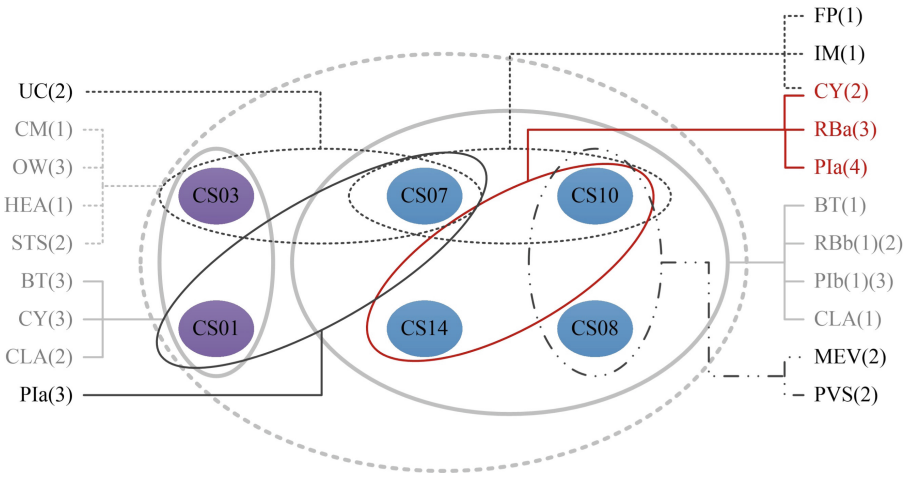


Fig. 9. Additional subsets in the third cluster of the case studies.

5 Conclusions

This study analyzed the use of the One-Stop Shop business model for improving building energy efficiency. Based on fourteen case studies across Central Europe, the relationships among variables belonging to three domains are investigated: distinctive features of the business model, characteristics of the buildings to be refurbished, and nature of the efficiency-related works. According to the above variables, the Rough Set approach enabled us to cluster the case studies into a few groups with well-defined boundaries and several further subsets that are vague, fuzzy, and often intersect each other.

The OSS BM is used equally by publicly-owned organizations and semi-public bodies, private non-profit entities, and private for-profit companies. The single contractor that takes care entirely of the efficiency improvement works - namely, the interface between the property owner and the other players - was expected to be often an Energy Service Company. It turns out that the role is played mainly by private entities other than the ESCos, especially construction companies, seldom architecture firms. Nevertheless, the presence of an ESCo as the contractor is clearly related to the exploitation of incentive measures meant to improve the energy performance of the building stock.

The OSS BM is chiefly used for the purpose of refurbishing outdated multi-family residential buildings, especially condos with a reinforced concrete load-bearing structure, built between the fifties and the seventies, likely characterized by poor insulation and barely efficient heating systems. Building size is highly variable; most cases are below 10,000 square meters, though a few case studies are characterized by a net floor area twice the above threshold. The buildings of the case studies are relatively not homogeneous as far as the starting energy rating band and energy performance index are concerned. Some of them were low-tier buildings relating to energy performance, as they were rated from G to E before the renovation work. Contrary to the expectations, others were mid-tier facilities rated D. Interestingly, the rating band after renovation is not strictly related to the one before. Thus, most buildings rated D before being renovated

do not make it through the B rating band after the works are completed, and one ends up gaining the C rating band only. Notable is also the case of an E-rated building that shifts simply to the D-rating band once the renovation is complete. Only about a fifth of the refurbished buildings are awarded the A-rating band.

The preferred renovation works involve building insulation, cladding, and heating systems. In several case studies, energy refurbishment is limited to the above domains. That is enough to reach an acceptable energy performance, which can be identified with the B and C energy rating bands. Occasionally, energy refurbishment is pursued by installing or improving other systems, especially mechanical extract ventilation or photovoltaic panels. That is essential to reach the highest energy performance, namely, the A energy rating band and an energy performance index lower than 40 kWh/m2 y, regardless of the starting rating band and the initial performance index. The renovation works seldom involve components such as cooling, solar thermal, and rainwater harvesting systems.

The analysis performed here lends itself to be extended to the other innovative BMs, the rise and development of which have been stimulated by the legal framework set at the EU level, as well as by the coherent incentive measures adopted by member countries. The forthcoming steps of the analysis in this field should be focused on comparing the pros and cons, strengths and weaknesses of the OSS and the other BMs to identify which one is best suited to pursue the energy refurbishment of the building stock.

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Creative Culture-Led Strategies for Sustainable Innovations: The Multidimensional Valorisation Project of the Pioppi Living Museum of the Sea, Italy

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Abstract. The role of eco-museums, and public aquariums, as cultural attractors and generators of socio-economic impact on the territories and communities in which they operate, shows how the analysis and comparison of the various European experiences highlight the modernity of Anton Dohrn's ideas and the creative strategies that have determined the virtuous reactions triggered in other contexts. The reinterpretation and application of the proposed innovation strategies were reinterpreted in the management of the Museo Vivo del Mare in Pioppi (Pollica, Salerno, Italy), set in the Italian context of public aquariums and eco-museums strongly linked to their territorial dimension. The decision-making process developed in this study allowed the identification of policies, approaches, and tools for the maximisation of the cultural impact of multidimensional valorisation processes. Implementing Multi-Criteria Analysis (MCA) techniques, it was possible to identify the preferable scenario and outline the corresponding development strategy.

Keywords: Eco-Museum · Cultural Heritage · Multi-Criteria Analysis (MCA)

1 Introduction

In Italy, the cultural and creative supply chain proves to be fundamental in developing national human and territorial capital, accounting for 5.6% of the added value of the entire Italian economy and 5.8% of employment [1]. These results translate, in a global dimension, into 3.1% of world GDP and 6.2% of the workforce, achieved despite the problematic two-year period of the Covid-19 pandemic, which led to a loss of general turnover, a contraction of employment and a crisis in the cultural and creative sector, to which the European Union responded with the Creative Europe Programme (2021–2017), allocating 2.44 billion euro to support the sector [1].

In addition, a key role from an economic perspective is played by the models of financial support through private funds for the valorisation of cultural heritage, widely

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adopted in the tax systems of several European countries: in France, donors can deduct up to 66 per cent of a donation from their income tax; in Germany, contributions for art and culture can be deducted up to 20 per cent of total income or, for private companies, up to 4 per thousand of annual turnover; in the United Kingdom, there is a general rule that establishes the principle of tax exemption for donations benefiting certain national museum institutions and, limited to natural persons, these acts of donation entail the advantage of the limit placed on the annual tax deduction on their income; in Spain, the deduction is around 35% [2].

In Italy, cultural patronage is also facilitated by the Bonus Art, which since 2014 has allowed private individuals to invest in the public heritage while receiving a 65% tax deduction from the State, thus greatly encouraging the synergy between the profit and non-profit worlds.

In the policies for the valorisation of cultural heritage, particular attention is paid to the role and contribution of museums for their potential to mobilise economic resources and to be drivers in urban and territorial regeneration processes, both when they belong to or are under the protection of a local administration, and when they are managed by a national authority or are private [3]. In recent years, valorisation strategies based on collaboration and dissemination of museum activities between cultural institutions, overcoming competition and conflicts, pursuing cooperation, and sharing tangible and intangible resources are gaining importance [4].

In this perspective, there is a need to develop a shared cultural enterprise strategy for museums, understood as innovative systems of cultural production capable of responding to the different demands of tourists and citizens and aimed at building a common language, able to dialogue with institutions and to enhance and safeguard the specificities of the environmental and cultural contexts in which they operate [5].

This need is particularly valid for ecomuseums, which require strategies and tools related both to their scientific and experimental research activity and as cultural enterprises. Public aquariums, which can be configured as a particular type of ecomuseums, historically based on their exhibits' attractiveness and scientific relevance, also fall into this con-context. However, the proposed study showed how these characteristics often proved insufficient for their survival, especially if not accompanied by adequate entrepreneurial creativity and the ability to build and maintain territorial links with the context in which they carry out their activities.

The contribution develops a reflection on the role of ecomuseums and, in particular, of aquariums, outlining a methodological approach aimed at identifying a valorisation strategy for the aquarium of Pioppi, in the National Park of Cilento, Vallo di Diano and Alburni, in the municipality of Pollica, in the province of Salerno (Italy). Starting from an analysis of the Italian context of public aquariums and a comparison of the various European experiences, particular attention was paid to the valorisation strategy promoted by Anton Dohrn for the Napoli aquarium in Italy, reinterpreted in the definition of the MuSea, the "Museo Vivo del Mare in Pioppi", which is one of the twenty-two aquariums currently active in Italy.

The contribution is therefore organised as follows: Sect. 2 is dedicated to Materials and Methods, in which the role of aquariums in Europe and the stages of the proposed

methodological process is made explicit; Sect. 3 faces the case study; Sect. 4 describes the results; Sect. 5 is reserved for the discussion of the results and conclusions.

2 Materials and Methods

2.1 Aquariums in Europe and the Creative Strategies of Anton Dohrn

The analysis of the development of public aquaria in Europe - from diffusion to decline, up to the current situation - makes it possible to explicate the causes and current conditions of decline, but also the need for innovative approaches essential for the operation of contemporary aquaria, with particular attention to the Italian situation.

The spread of aquariology and aquaristics to the public [6] is due to some relevant assumptions, such as: technological and scientific progress, insofar as for marine biologists and naturalists, aquariums were the perfect tool for observing aquatic fauna and flora, and technical skills enabled the reproduction of such habitats in captivity [7]; the periodic organisation of Universal Expositions - in close connection with technical-scientific development - with the aim of displaying their level of avant-garde and innovation; the accessibility of coastal areas, made reachable by a large part of the population through the new railway lines; collectivism, related to the fashion of collecting objects, which exploded in the field of private aquarium keeping [6].

From the beginning of the second half of the 19th century, in the main European centres, the first large city aquaria began to open to the public by civic but also private initiative. In the second half of the 19th century, 14 public aquaria were established: the first was the Fish House in London (1853–1855), followed by the Jardin Zoologique d'Acclimatation in Paris (1860–1877) [8], the Viennese Aquarium Salon in Vienna (1860–1864), the Marine Aquarium Temple in Hamburg (1864–1930) the Berlin Aquarium (1869–1910), the Crystal Palace in Sydenham in London (1871–1941) [9], the Brighton Aquarium (1872-in activity), the Stazione Zoologica in Naples (1874-in activity), the Manchester Aquarium (1874–1876), Dr. Cocker's Menagerie in Blackpool (1875–2010), the Royal Aquarium in Westminster (1876–1903), the Scarborough Aquarium (1877–1925) [10], the Tynemouth Aquarium and Winter Garden (1877–1898), the Artis Aquarium in Amsterdam (1884-in activity).

Each of the listed aquaria was analysed considering some significant criteria: location, period of activity, type of facility and reason for closure. Observing the collected data, it was possible to make some considerations on the development phases of the phenomenon and the characteristics that contributed to the longevity and vitality of these facilities. In fact, the datum common to most of the historical aquaria highlights among the reasons for the closure, followed in some cases by the demolition of the building that housed them, the low financial return.

The progressive loss of attractiveness for visitors, with the consequent condition of economic unsustainability, led, in turn, to the conversion of aquaria into more profitable activities (in 42.9% of cases) or to closure due to bankruptcy (in 28.6% of cases).

Furthermore, in the first decades of its development, aquarists also brought with them logistical and functional advantages useful for scientific research, such as the possibility of observing marine organisms at close quarters, with the development of new instruments - including underwater cameras and diving equipment - it was no longer

essential for naturalists and marine biologists to recreate aquatic ecosystems in tanks in order to conduct their studies in the laboratory [6].

The only three historical aquaria still active today - Brighton, Amsterdam and Naples - have probably survived ephemeral fashions and economic obstacles for a variety of reasons: for the Brighton aquarium, it was the citizens themselves who contributed to the enhancement of the public aquarium, consolidating its attractiveness as a historical tourist destination; the aquarium in Amsterdam [11] was integrated into the city's enhancement and management actions, also developed in relation to the zoological park and other cultural and natural facilities; the aquarium in Naples, known as Stazione Zoologica, was activated with the intention of enhancing scientific research, and developed thanks to the creative and entrepreneurial skills of its founder and director, the biologist Anton Dohrn [12].

In particular, the success factors - exogenous and endogenous - acknowledged to the valorisation strategy promoted by Dohrn can be summarised as follows [13]:

- the creative and entrepreneurial capacity of the founder;
- the ability to design a museum in innovative terms;
- the ability to bring together and stimulate various scientific talents;
- a strong motivation of the collaborators towards a common goal;
- the application of a paradigm of great scientific value: the Darwinian theory;
- the development of a lively cultural climate;
- the possibility of increasing international relations and exchanges;
- the aptitude for interdisciplinary study;
- the realisation of a building characterised by high aesthetic quality, stimulating scientific creativity.

The combination of these various factors meant that the Zoological Station adopted an organisational and management model characterised by a number of peculiarities, such as: the free and autonomous organisation of the research work; elasticity of the organisation; a position in the vanguard and openness to new technologies; the absence of compartmentalisation in the division of tasks; apoliticality, hospitality, secularism, tolerance, continuous exchange; personal and informal connections between scientists on an international level; interdisciplinarity and collaboration between the natural sciences and art.

There are currently twenty-two public aquaria in Italy, of varying vocation and size [14–18]. The regions with at least one public aquarium are mainly those with a Mediterranean character and a maritime vocation: the record is held by Tuscany, which has six public aquaria. In fact, the aquariums are mainly marine - in 72.7% of cases - but 13.6%, consistent with the reference territory, host fauna and flora typical of lake or river habitats, and the same percentage has both freshwater and saltwater tanks.

Within this variegated aquarium landscape, some distinctions can also be made in relation to the management and administrative structure: private ownership characterises 27.3% of aquaria, while 54.5% belong to a public body; 36.4% of living museums are managed by private companies, while non-profit organisations manage 31.8%, and only 13.6% are publicly managed.

2.2 A Decision Support System for the Pioppi Aquarium Enhancement

The multidimensional valorisation project MuSea Museo Vivo del Mare has been structured by elaborating a decision support system articulated in four main phases [19]:

1. Knowledge of the territorial context and identification of the stakeholders;
2. Identification of policies and tools for the maximisation of the cultural impact and elaboration of alternative scenarios;
3. Multicriteria evaluation and selection of alternative scenarios;
4. Explication of the valorisation strategy and programming of activities (Fig. 1).

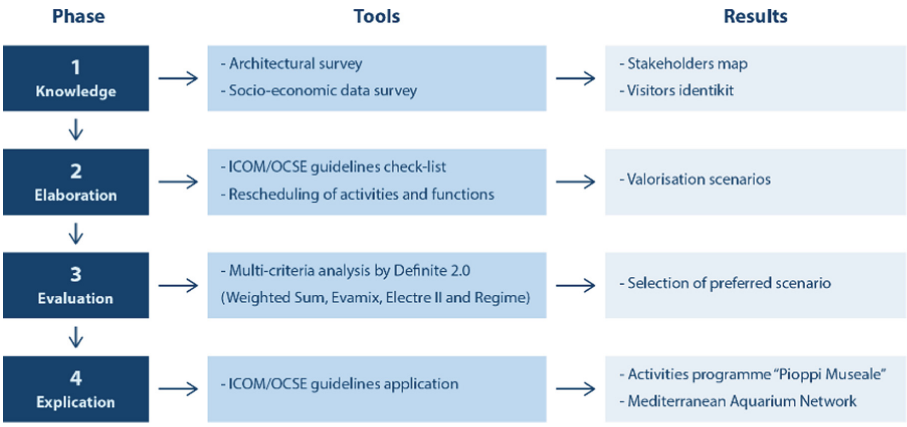

Fig. 1. A Decision Support System for the Pioppi aquarium enhancement strategy.

The first phase analysed the village of Pioppi and the MuSea, the aquarium housed in the historic building of Palazzo Vinciprova, considering both the historical and territorial, as well as the architectural and cultural aspects. In particular, the methodological process was carried out on the survey and representation of the building housing the aquarium, necessary to put forward a multidimensional valorisation proposal also aimed at developing a reorganisation of the exhibition spaces in relation to the new functions and activities envisaged in the valorisation proposal.

The knowledge of the context and of the cultural asset was articulated considering also the way in which the exhibition spaces are managed, analysing the type of visitors and the network of stakeholders that can be involved in the decision-making process, with the aim of preparing a valorisation strategy capable of maximising the cultural impacts of the aquarium.

The different types of information collected in the first phase of the research were complemented by identifying possible local administrative policies and instruments available to museums and verifying their implementation under the specific conditions of the case study analysed.

The data obtained and analysed were relevant for the planning of museum activities and for the elaboration of valorisation scenarios, which were developed on the basis of a

number of significant components: types of admission tickets, local events that could be activated with the involvement of the museum, stakeholders involved, activities carried out, professional resources employed, sponsors engaged and expected results.

Finally, in the evaluation phase, the constructed scenarios were subjected to a structured multi-criteria analysis with the support of Definite 2.0 software to establish an order of preference and select the alternative to elaborate the enhancement strategy.

3 The Case Study: "MuSea", an Ecomuseum for Pioppi, Italy

The ecomuseum under study, the MuSea, is in Pioppi - a village on the Cilento coast in the province of Salerno, in the highly touristic and naturalistic context of the Cilento, Vallo di Diano and Alburni National Park - and together with the Living Museum of the Mediterranean Diet, is housed in the historic Palazzo Vinciprova (Fig. 2).



Fig. 2. The case study: MuSea, Pioppi (Italy)

The MuSea is currently owned by the municipality of Pollica, and its management is entrusted to the Legambiente Onlus association, which in turn uses the Cooperativa Minnelea to organise its activities. The MuSea offers the possibility of purchasing a ticket online, including a visit to both mu- seas of Palazzo Vinciprova; an annual subscription can be purchased, and a guided tour service is available. MuSea's activities mainly consist of three didactic workshops dedicated to school groups, including preschool and secondary schools.

The data collected on the number of admissions show that the period of highest attendance coincides with the spring months. Looking at the attendance figures for the last few years of the museum's operation, the trend has been positive from 2016 onwards, when the latest restoration work was completed. However, the same data confirms the negative effects of the Co-vid-19 pandemic, reporting a drop in admissions in 2020 [20].

The case of the Pioppi ecomuseum is paradigmatic in terms of both criticality and potential: it is one of the Italian aquariums owned by a public body - accounting for the majority (54.5%) - and managed by a non-profit organisation (as in 31.8% of cases). Moreover, its insertion in the context of a small village - but at the same time strongly characteristic and sensitive to the processes of tourism - underlines its territorial vocation and its capacity to generate positive impacts on the local community. Moreover, the peculiarities of the context allow the elaboration of development scenarios able to

enhance the different roles that the MuSea could potentially assume in the process of active co-engagement of the different local resources.

4 Results

The application of the methodological process described in Sect. 2 led to the definition of a new programme of activities and the proposed establishment of a collaborative network between Italian public aquaria in an incremental multivariate perspective.

4.1 Knowledge of the Territorial Context and Identification of Stakeholders

The historical and territorial framework of the village of Pioppi was structured by analysing historical memoirs [21], monographs [22–24], drawings and documents relating to the recent restoration project of Palazzo Vinciprova [25], and socio-economic data and trends [26], as well as through the inspections and surveys carried out. In particular, an integrated survey campaign was carried out for the building housing the MuSea - with image-based and range-based techniques - which allowed the building's two-dimensional and vectorial graphic restitution and detailed architectural and material knowledge.

The survey of socio-economic data and the description of the administrative-managerial organisation of the museum were based on the consultation of recent balance sheets [20, 27] prepared by the managing body and the museum management. The different surveys allowed the construction of an overall picture of the museum's functioning, including information on visitor numbers and flows, services offered, exhibition content, staff employed and external companies and structures involved in the activities.

From the different analyses carried out, it was possible to structure a map-pa of the stakeholders involved and potentially involved in the museum activities. The identification of the stakeholders, i.e. the groups of individuals or individuals who can influence or be influenced by the achievement of the museum's objectives [28], allows, on the one hand, to understand the socio-economic environment in which the museum is contextualised, and on the other hand to identify the resources and possibilities for its development [29, 30] based on bottom-up and inclusive strategies to maximise the cultural impact [31–34].

The stakeholders of the MuSea that have been identified (Fig. 3) correspond primarily to the territorial authorities, represented not only by the municipality of Pollica - of which Pioppi is a hamlet - but also by the Province of Salerno and the Cilento, Vallo di Diano and Alburni National Park Authority, responsible for the adoption of administrative policies in collaboration with the museum institutions. Fundamental to the scientific interest and cultural matrix of the ecomuseums is also the relationship with universities and research centres, in which the two largest universities in Campania - the Federico II in Naples and the University of Salerno - as well as the Anton Dohrn Zoological Station, occupy a leading position.

To promote collaboration between cultural institutions and to elaborate a shared strategy, not only the other Italian public aquariums are privileged interlocutors, but

also the National Association of Scientific Museums, as well as the nearby and well-established Archaeological Park of Paestum and Velia. Naturally, the stakeholders that can be involved in MuSea's activities include local businesses - in their forms of accommodation, commercial and catering activities, and farms - and cultural associations operating in the area, as well as the local community itself. Finally, the visitors of the MuSea have also been included in the stakeholders' map. All the actors identified are thus interconnected by relationships of mutual influence and direct or indirect cooperation.

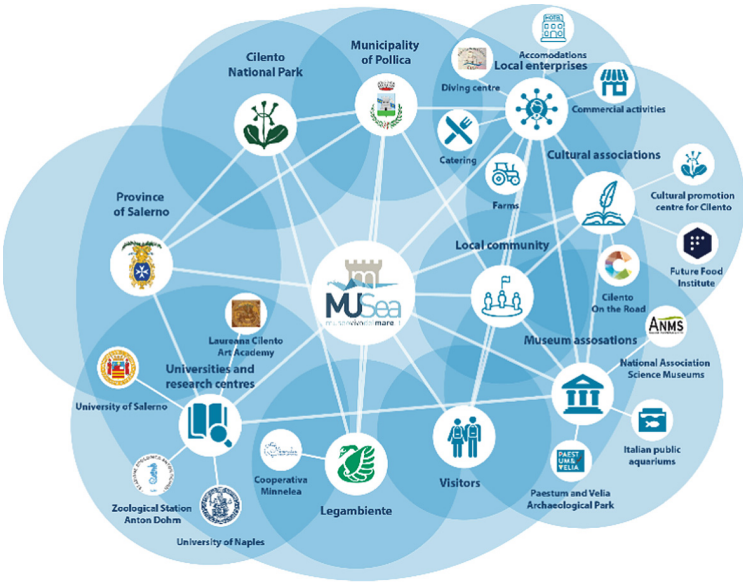

Fig. 3. Stakeholders map

Furthermore, within the stakeholder group represented by the visitors, a number of relevant categories are distinguished: schoolchildren, travellers, tourists and naturalists. The parameters used for the selection concerned the period in which the visit takes place - in a particular season or throughout the year - and the type of entrance - single or in a group; the demand for activities expressed by the visitors - such as educational activities, exhibition quality and scientific research tools - and the services that can be offered by the museum - guided tours, educational workshops, excursions, thematic exhibitions, events, seminars - and consequently the necessary museum spaces - exhibition halls, book-shops, library, laboratories and multi-purpose halls - and the external services supporting the activities - agritourisms, educational farms, refreshment facilities, commercial activities, natural parks, other museums and research centres.

4.2 Identifying Policies and Instruments for Maximising Cultural Impact and Developing Alternative Scenarios

Strategies to maximise cultural impact articulate and implement museum programmes of activity through policies and instruments available to both museum institutions and

public administrations, which have been defined according to the guidelines of the International Council of Museums (ICOM) and the Organisation for Economic Co-operation and Development (OECD) [2].

The guidelines identified five main themes:

1. Harnessing the power of museums for local development;
2. Enhancing the role of museums in urban regeneration and community development;
3. Stimulating culturally aware and creative societies;
4. Promoting museums as spaces of inclusion, health and well-being;
5. For each of the themes, actions and possible policies were identified and analysed through a check-list [2], resulting in a classification based on the relative level of criticality and potential, indicating which are to be introduced, which are to be increased and which are to be enhanced (Fig. 4).

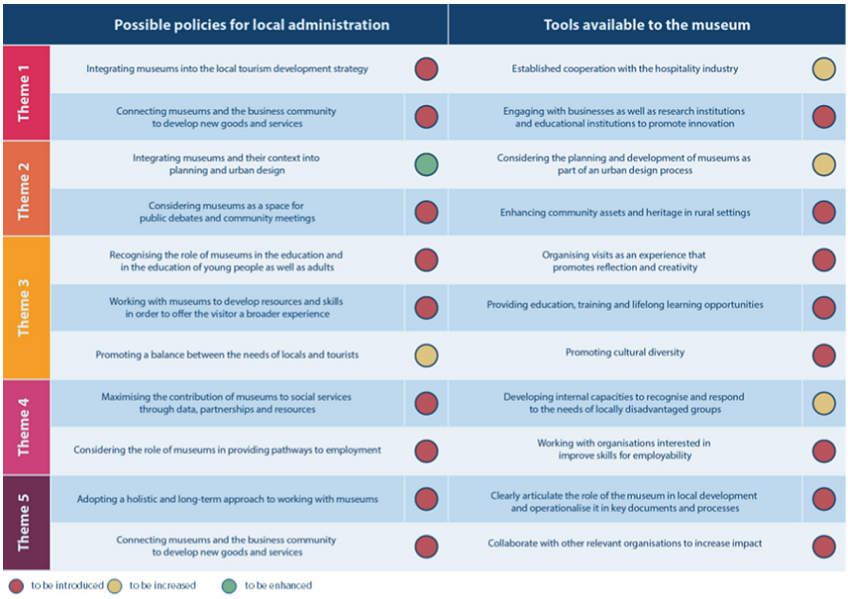

Fig. 4. ICOM/OECD guidelines check-list.

The result is a poor picture of the current condition in terms of administrative policies and strategies implemented by the museum institution, especially if one considers the museum's educational role and contribution to employment. Indeed, its role is in a passive position within the local tourism and economic scenario, indirectly suffering its positive impacts without generating further impulses in terms of new goods and services. The museum's integration into urban planning is less critical, thanks to recent initiatives undertaken by the municipal administration.

The knowledge of the processes being implemented and of the main stakeholders has made it possible to structure the planning of MuSea's activities that move according to the principles of innovation and digitisation of services, the elasticity of supply, synergy

between profit and non-profit, and museum outreach and collaboration with other cultural institutions. The activities are designed by identifying different modes of use (online or in-presence) dedicated to different categories of visitors in partnership with the mapped stakeholders. The programming of activities also aims at defining and enhancing the different vocations of which the MuSea is bearer: the tourist, the scientific and the territorial character.

The programme of activities, administrative policies, implementation tools and stakeholders involved have therefore taken on different modulations and articulations, according to three alternative strategic options (Fig. 5), each of which refers to a particular vocation that the ecomuseum potentially possesses. Three alternative strategic options were elaborated to identify the pre-feasible scenario, each based on a specific vocation attributed to the MuSea.

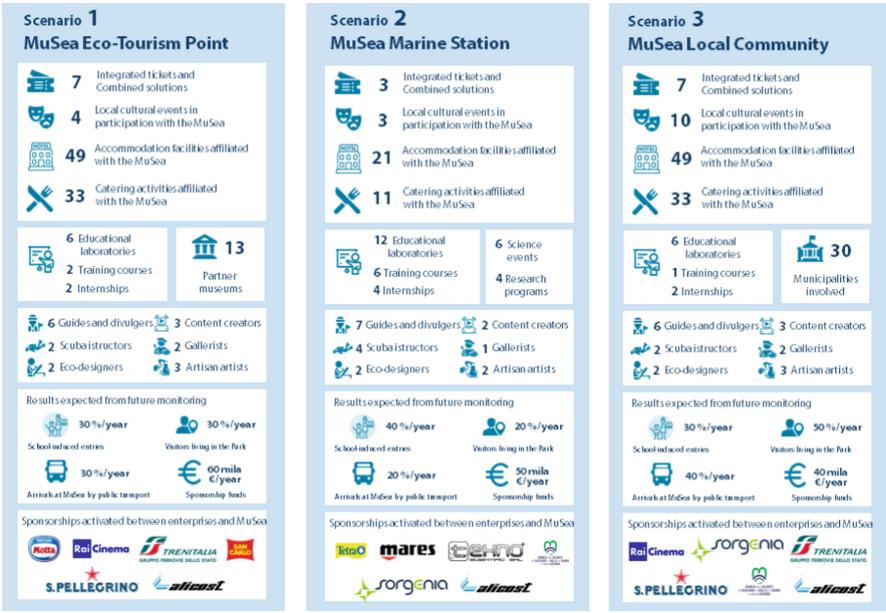

Fig. 5. Alternative scenarios.

In the first scenario (S1), the 'MuSea Eco-Tourism Point', emphasis was placed on the active participation of the Pioppi Aquarium in the development of sustainable tourism in the area, paying attention to the issues of the environment, climate risk, and the conditions of abandonment and depopulation of internal areas [35]. An entrance fee plan has been drawn up to provide a satisfactory number of combined solutions, encouraging collaboration with other museum institutions in Cilento National Park and neighbouring municipalities and involving hotels and restaurants; the educational and training offer has been expanded with respect to the status quo, but it is expected that economic resources will be used to a greater extent in the recruitment of professional profiles needed to carry out attractive activities mainly aimed at tourists and travellers;

the sponsorships that can be activated between private companies and the MuSea involve important national companies in the food, transport and cultural entertainment sectors, potentially interested in investing [36].

In the second scenario (S2), the 'MuSea Marine Station', the scientific nature of the particular type of museum institution that the Pioppi aquarium represents was emphasised, with an emphasis on its training and educational role in the protection of the marine ecosystem and biodiversity, as well as on the potential scientific research activities [37] that can be conducted at the new laboratories proposed to be located in the Palazzo Vinciprova building and in collaboration with the other aquariums in the network. Human and financial resources will therefore be concentrated on activities dedicated to educational laboratories, training courses and workshops, with a more targeted use than collaborations with tourist facilities; in this scenario, sponsorships will involve more companies specialised in the aquarium and technology sectors.

In the third scenario (S3), the 'Musea Local Community', the museum's ability to create territorial links and to become a promoter of local culture is encouraged, re-proposing some of the strategies envisaged for the eco-tourism scenario, but with a greater focus on the interests and needs of the local community [2]; the collaboration with companies and accommodation facilities located in the neighbouring municipalities becomes particularly important, and the distribution of resources in the activities carried out outside the MuSea premises grows accordingly; sponsorships could, in this case, involve both big national companies and solid local realities.

4.3 Multi-criteria Analysis, Selection of Alternative Scenarios and Valorisation Strategy

To identify the preferred strategic alternative, it was essential to proceed with a multi-criteria evaluation, defining the objectives to be maximised and the respective relevant criteria to be used to describe and analyse the options.

It proved useful to make use of the decision support provided by the Definite 2.0 software [38], which offers the possibility of comparing the results of the evaluation carried out with the Weighted Sum, Evamix, Electre II and Regime methods [39–42].

An evaluation matrix was then structured in which the criteria are made explicit by indicators, for each of which, in addition to defining its value as it stands, forecasts were made for each of the hypothesised strategic scenarios.

The second step, necessary to homogenise information of different natures, consisted in standardising all the components of the evaluation matrix in a range between 0 (zero) and 1 (one).

This was followed by the 'weighting', i.e. the assignment of weights to all criteria to reflect their relative importance in the evaluation process: in this case, the weighting was based on the classification returned by the checklist of ICOM's selected themes, thus delineating three groups of weights, consisting of the criteria linked to the valorisation objectives and placed in descending order of importance, attributed by applying the expected value approach.

To examine the alternative options ranking, applying the four multi-criteria analysis methods of the Definite 2.0 software made it possible to reason in an integrated manner and verify the robustness of the preferred scenario.

The following objectives were defined for the group of scenarios outlined:

1. integrating the museum's role in local development processes;
2. valorising the museum's activities in territorial regeneration programmes;
3. stimulating culturally aware and creative communities.

For each objective, relevant criteria were defined to analyse the options. Respectively, the first objective identifies: to develop cultural strategies for the valorisation of local tourism (C1); to activate collaborations and synergies with tourism and accommodation activities (C2); to collaborate with the local, national and international business community to develop new goods and services (C3).

The second objective considers: to integrate the museum into a broader process of territorial development (C4); enhance the assets and heritage of the local community (C5).

The third objective includes: to develop resources and skills to offer visitors an immersive experience in the museum (C6); to strengthen the active involvement of young people in the museum's didactic and educational activities (C7); to offer education, training, and lifelong learning opportunities at the museum (C8); and to foster a balance between the needs of the local community and those of tourists (C9).

In the evaluation matrix (Fig. 6), each criterion is expressed by one or more indicators, the value of which has been made explicit for each of the three scenarios considered.

After the standardisation phase, the 'weighting' of the criteria - based on the classification returned by the ICOM checklist - outlined three groups of weights, in descending order of importance: C1, C5, C6, C8; C2, C9; C3, C4, C7.

The weighted sum method allowed the alternative options to be analysed in order of preference, resulting in: S3 (0.72), S2 (0.69), S1 (0.66).

The robustness check, conducted by changing evaluation methods (Evamix, Electre II, Regime), confirms the result previously obtained as the preferred strategic scenario but also shows a not particularly significant difference between the values of the three options. In particular, the results identify the following rankings (Fig. 7):

– for Evamix method: S3 (0.38), S2 (-0.01), S1 (-0.37);
– for Electre II method: S3 (1), S2 (2), S3 (2);
– for Regime method: S3 (1), S1 (0.5), S2 (0).

The preferred strategic alternative was found to correspond to the MuSea Local Community scenario, thus favouring the territorial vocation of the Pioppi aquarium, and this result is also appreciable from the sensitivity analysis, carried out by changing the weight attributed to each criterion and comparing the obtained results through other multi-criteria methods.

Goals	Sub-Goals (criteria)	Indicators	Unite of measure	Value as it stand	Source	Year	Direc-tion	S1	S2	S3
Integrating the role of the museum in local development processes	(C1) Developing cultural strategies for the enhancement of local tourism	(I1) Annual number of local cultural events in which the museum is involved	No./year	1	Legambiente Report	2021	>	4	2	10
		(I2) Annual number of seasonally active activities and services	No./year	3	Legambiente educational proposal	2022	>	6	6	6
		(I3) Annual number of year-round activities and services	No./year	0	Legambiente educational proposal	2022	>	5	5	5
		(I4) Annual number of activities and services available on the museum's online platform	No./year	1	Museum web site	2022	>	5	5	5
		(I5) Number of offers of combined packages of museum admission and other cultural activities	No.	1	Museum web site	2022	>	7	3	7
	(C2) Activating collaborations and synergies with tourism and accommodation activities	(I6) Number of accommodation establishments cooperating permanently with the museum	No.	0	Museum web site	2022	>	49	21	49
		(I7) Number of catering businesses that collaborate permanently with the museum	No.	6	Museum web site	2022	>	33	11	33
	(C3) Working with the local, national and international business community to develop new goods and services	(I8) Annual funding obtained from sponsorships of companies or external bodies	€/year	nd	Museum administrative report	2023	>	60000	50000	40000
Enhancing museum activities in territorial regeneration programmes	(C4) Integrating the museum into a wider process of land development	(I9) Number of municipalities in the provincial territory involved in the museum activities	No.	1	Legambiente Report	2021	>	30	23	30
		(I10) Number of scientific, cultural and social institutions from other municipalities or provinces, which collaborate with the museum	No.	1	Legambiente Report	2021	>	20	13	20
		(I11) Number of public aquariums in the Mediterranean area collaborating with the museum	No.	1	Legambiente Report	2021	>	6	6	6
		(I12) Annual percentage of visitors reaching the museum by soft mobility or public transport	%/year	nd	Visitors questionnaire	2023	>	30	20	40
	(C5) Valuing local community assets and heritage	(I13) Number of volunteers involved in the management and maintenance of the museum and its premises	No.	0	Legambiente Report	2021	>	2	6	8
		(I14) Number of external venues hosting services or activities organised by the museum	No.	0	Legambiente Report	2021	>	3	3	3
Stimulating culturally aware and creative communities	(C6) Developing resources and skills to offer the visitor an immersive museum experience	(I15) Number of museum employees in charge of digitising content and managing the online platform	No.	0	Museum administrative report	2022	>	3	2	2
		(I16) Number of museum employees engaged in activities at external locations	No.	0	Museum administrative report	2022	>	6	5	8
	(C7) Strengthening the active involvement of young people in the museum's didactic and educational activities	(I17) Annual number of educational workshops for schools offered	No./year	3	Legambiente educational proposal	2022	>	6	12	6
		(I18) No. of museum employees involved in outreach and education	No.	2	Museum administrative report	2022	>	3	5	3
		(I19) Annual percentage of school induced entries	%/year	nd	Museum administrative report	2023	>	30	40	30
	(C8) Providing education, training and lifelong learning opportunities at the museum	(I20) Annual number of undergraduate and postgraduate internships activated by and/or at the museum	No./year	0	Legambiente Report	2021	>	2	4	2
		(I21) Annual number of training courses and scientific seminars organised by and/or at the museum	No./year	1	Legambiente Report	2021	>	2	4	2
	(C9) Favouring a balance between the needs of the local community and those of tourists	(I22) Number of museum employees engaged in activities in the territory	No.	0	Museum administrative report	2022	>	5	6	6
		(I23) Annual percentage of visitors living in the Park	%/year	nd	Visitors questionnaire	2023	>	30	40	30

Fig. 6. Table of objectives, criteria and indicators of the current state and alternative scenarios.

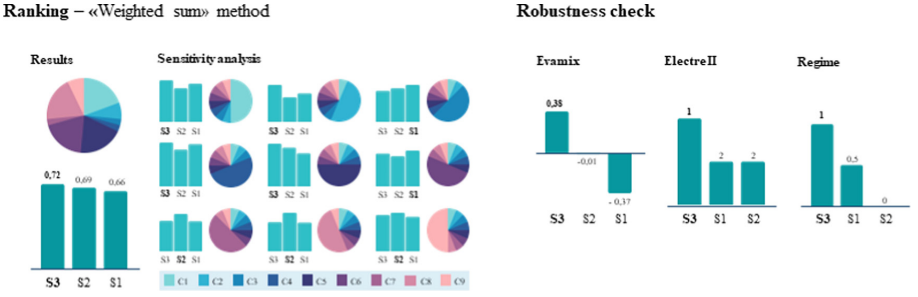

Fig. 7. Results with weighted sum method and robustness check with Evamix, Electre II and Regime methods

5 Discussions e Conclusions

The evaluation phase of the constructed strategic development scenarios made it possible to identify the preferred alternative able to maximise the cultural and economic impacts, consistent with the application of the ICOM/OECD guidelines.

The programme of activities "Pioppi MuSEAle" and the Network of Mediterranean Aquariums are developed based on stakeholders' identification and considering four categories of visitors. Indeed, it was possible to draw up a programme of activities of the MuSea, tailor-made on selected target groups and resources that can be activated.

Innovation and digitisation of museum content are considered a priority, which can be translated, for example, by a more significant presence of the museums on social channels or by the proposal of visit experiences conducible through web platforms; these new ways of enjoyment are combined with the principle of elasticity of the services on offer, also in terms of tariffs, thus preparing subscriptions and integrated solutions. Therefore, the Pioppi MuSEAle programme was developed with these inputs and articulated in eight different activities according to a creative strategy [43].

The programme was calendared annually to distribute the activities, concentrating them from time to time in the months in which there is the most significant demand from the main target groups, but without creating time gaps that would support an ineffective seasonality of the museum offer.

Furthermore, to carry out the new activities, it was necessary to identify six new professional profiles to act as a bridge between the sea, the territory and the museum: Thus, the figure of the local guide is indicated for the organisation of activities focusing on historical-cultural themes; the underwater guide, for the supervision and support for visits and excursions organised at sea; the gallery manager, for the care of the art gallery and the promotion of cultural events; the artisan artist and the eco-designer, for participation in the gallery exhibitions, creative workshops, and activities focusing on historical-artistic themes.

The new programme changes the territorial and spatial organisation of the MuSea and its activities, expanding it both on a municipal and provincial scale and in its articulation within Palazzo Vinciprova. Furthermore, the activities carried out outside the MuSea premises - thematic tours and underwater excursions - will help spread the area's cultural value and create social and economic links with other municipalities in a virtuous involvement of the respective communities.

Following the principles of collaboration and museum dissemination, the establishment of a Network of Mediterranean Aquariums is proposed, identifying them among the mapped contemporary Italian aquariums according to selection criteria that consider both their specific vocations - educational, scientific or even attractive - and quantitative parameters, which are comparable and compatible with those of the MuSea. Specifically, they looked at the active commitment to scientific research and the protection of the marine ecosystem of the Mediterranean Sea; at the dimensional and quantitative characteristics of the contents of the living museums and host structures; at the administrative and management structure of the various sectors involved in museum activities; and at the solidity of the economic system and stability of the financial resources, ensured by funds, sponsors or receipts. Tools and strategies at the disposal of the Network were then defined: provision of a website dedicated to the Mediterranean Aquarium Network for the offer of multimedia content, online services and information; visitor loyalty plans, such as subscriptions and membership cards, and discounted rates for admissions to the various aquariums of the Network; travelling festivals and exhibitions and tours, stage trips and "sustainable cruises" reaching the locations included in the Network events and initiatives to raise the awareness of communities and visitors on the protection of the biodiversity of the territory and the marine ecosystem; workshops, intensive courses and seminars dedicated to the training and refresher courses for aquarium operators and

staff; the drafting of a periodical magazine with a scientific and popular character, to be published in digital form and collections of physical copies at the aquarium bookshops.

The multidimensional valorisation project Pioppi MuSEAle aims to give the local aquarium, as a place of culture and research, an essential role in territorial and sectorial development based on the structuring of a decision-making process aimed at developing strategies to maximise the cultural impact using approaches and techniques from multi-criteria analysis, to outline a programme of activities for the valorisation of the cultural asset.

This contribution highlighted the role of the multiple components determining the correct and stable functioning of ecomuseums and museum institutions: entrepreneurial creativity, institutional cooperation, synergy with public administration, public-private partnership, and territorial interconnections.

Through the application of the ICOM/OECD guidelines, the aim was to trigger a process of maximising the cultural and economic impact produced by a public aquarium for the local community in terms of growth and mobilisation of resources and territorial development.

The research also highlighted the multi-scalarity and multi-dimensionality involved in impact maximisation and resource enhancement, both in the decision-making and implementation phases.

The structured decision-making process could be replicated using methods that support stakeholders' participation and active involvement, including assigning weights to criteria by different groups of actors to consider the other points of view and identify possible conflicts in different policy scenarios.

The tried and tested methodological process, together with the advanced reflections and results of the multi-criteria evaluation, represents a starting point for the further design developments of the strategic scenarios, recognising as a prerequisite the preferability of the option that emphasises the territorial character from which to trigger direct participation and active involvement of stakeholders.

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Regenerating the Landscape Through the Co-production of Complex Values

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Abstract. Studies and reflections about landscape identify research perspectives that interpret the landscape as a fundamental resource for activating processes of local development. This is an issue of significant importance because the landscape represents the essential resource with which it is possible to compete in the global competition. Landscape can be considered the "attractor" element that gives territories a differential advantage.

The paper explores a field of reflections that help answer some key issues related to improving the quality of decision-making processes to build a more desirable and sustainable future involving stakeholders and local communities and support the co-production of new complex values.

The hybridization processes that have characterized the 'Historic Urban Landscape' represent a prospect of regeneration because the integration between the multiple dimensions, the dialogue with the context, and the synergetic and symbiotic links can promote new forms of vitality and generate tangible and intangible values. Preserving the landscape is no longer sufficient, and an active and regenerative approach is needed. With reference to the landscape of the Cilento, Vallo di Diano and Alburni National Park, the study proposes a development model for landscape regeneration oriented to integrate a trans-disciplinary and holistic approach with operational tools.

Keywords: Regenerative landscape · Complex Social Value · Mixed methods

1 Introduction

According to the Historic Urban Landscape approach (HUL) [1], the landscape is a complex, dynamic, and adaptive system based on relationships between humans and nature, in which ecological, economic, and cultural dimensions are strongly interrelated. From this perspective, the landscape is seen as a living system in which the existing relationships, synergies and dynamic symbioses between its components should generate new positive linkages to maintain its resilience over time [2].

In the current context, where the landscape is under tremendous pressure, innovative actions are needed to activate regenerative processes capable of maintaining virtuous processes or creating new ones. In this complex situation, the regeneration of collective

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memory and community ties is not enough, but it is necessary to work on recreating connections and meaning between natural, cultural, social, economic, and human aspects.

The HUL approach places heritage conservation within a new systemic vision that links tradition and modernisation, present and past, present, and future in a circular and synergistic perspective. Above all, it considers landscape change in a multidimensional space, emphasising the interdependencies and relationships between the various components and the whole. Therefore, in the HUL approach, conservation is oriented towards respecting the integrity of values and avoiding their alteration but assuming a general perspective of change [3].

The recognition of links, relationships and connections can therefore be interpreted as an indirect lever to promote synergies between different actors/institutions, through a creative integration between conservation and development, from a dynamic and proactive point of view [4]. Thus, the HUL perspective is based on relational principles and aims to integrate different types of values (economic, aesthetic, equity, etc.). The principle of relationality is the conceptual basis of the integrated conservation approach, which values the positive interaction between the different components of a system to determine an increase in the value of all elements. Therefore, an 'integrated' conservation project aims to consciously promote the complementarity of heterogeneous elements/components, seeking the specific conditions that determine a mutual valorisation [4].

In this vision, heritage conservation becomes a "productive activity" capable of generating added value in several ways: improving the quality of life by preserving the spirit of places, stimulating social cohesion, and as a condition for greater economic productivity. Emphasising innovation in conservation (in a dynamic perspective), the HUL approach resists standardisation and focuses on creative conservation for effective development (not only related to tourism).

The management system is, therefore, a key element in the conservation of existing values and the production of 'new' ones. Indeed, its role in the HUL approach is to prevent cultural heritage from remaining merely a testimony to an ancient past. Instead, it aims to generate meanings and sensations (beyond the aesthetic dimension) in the present, stimulating the production of relational values/links and transforming cultural values into civic values and conflicts into synergies.

The transition to the sustainable landscape development model should be based on specific local cultural resources and not only on technological innovations: that is, it should be based on a sound strategy that places the use of cultural resources as a central element of development [5, 6].

The implementation of HUL, therefore, requires not only technical tools but also a strong intellectual and critical process of interpretation and mediation between the different conflicting forces in search of a balance/equilibrium that unites different interests. Therefore, the successful implementation of HUL also depends on strong bottom-up support: a cultural base capable of stimulating cooperative approaches and circular thinking towards the achievement of the general interest.

To explore this new research perspective in a real context, the Cilento Labscape project, promoted by the Department of Architecture, University of Naples Federico II,

has set up a network of laboratories in the National Parks of Cilento, Vallo di Diano and Alburni, in the South of Italy, involving local stakeholders and communities.

The aim was to develop a new interpretive code for the landscape of the Park, based on local innovation, on the ability to organise knowledge of the territory according to systemic logic, on local creative development models that mix formal rules and spontaneous processes. The interaction between tangible components (such as physical infrastructures and services) and intangible components (such as territorial, cultural, and social networks) has made it possible to define the concept of "regenerative landscape" [7] for the National Park of Cilento, Vallo di Diano and Alburni as a complex space in which the issues of competitiveness and sustainability can be addressed, taking into account social cohesion, creativity, adaptive innovation and quality of life.

Based on the experience of the Cilento Labscape project, this paper proposes the integration of transdisciplinary and holistic approaches with operational tools to support the development of landscape regeneration models. More specifically, the second section presents the main lessons learnt from the Cilento Labscape project, the third section presents a development model for landscape regeneration oriented towards the integration of a transdisciplinary and holistic approach with operational tools, and the fourth section discusses the main conclusions.

2 A Regenerative Process for the National Park of Cilento, Vallo di Diano and Alburni

The National Park of Cilento, Vallo di Diano and Alburni has a high landscape value. The different forms of capital (tangible and intangible) characterise it and generate a flow of services that can promote the well-being of local communities.

It is an ambivalent territory in which characteristics that are often seen as negative (fragile, marginal, internal, weak, rural, abandoned, etc.) coexist with characteristics that identify significant potential (resistant, central, external, strong, urban, vital, etc.), highlighting contrasts, dialectical and conflictual processes. In particular, there is a constant dialectic between inland and coastal areas, with the latter tending to play a predominant but not dominant role, highlighting cultural and economic conflicts, but also revealing different approaches to the possible valorisation of resources recognised as significant.

The landscape of the Park is configured by processes of different speeds, identifying slow landscapes, whose rhythms are determined by reflective lifestyles, and fast landscapes, influenced by the effects of urbanity, which determine development paths that could be considered complementary and synergistic. Different spatial peripherality levels often coincide with different speeds of development, implemented by different methods that do not always correspond to homogeneous classifiable categories.

The landscape is also configured as a system of values, relationships and interactions between places and communities, declining individual specificities typical of each context, expressions of multidimensional networks of values and resources that require a close look, careful to grasp the main characteristics that they identify the differences and identify places, architectures, histories, stories of everyday life, material culture, life experiences, communities and systems of relationships, tangible and intangible, expression of landscape images sedimented in the cultural memory of each person and

a community. Each of these forms of capital is associated with a particular aspect of the landscape. In other words, this complex landscape is the combination and iteration of six landscapes: natural, manufactured, cultural, economic, social, and human. The specific character of the Park, its identity/attractiveness, is derived from the mutual combination of these landscapes (Fig. 1) [8]:

- The natural landscape consists of existing natural capital (biomass, biodiversity, ecological corridors, agricultural land, natural ecoservices, lakes, rivers, energy resources, etc.).
- The built landscape consists of infrastructures and systems of facilities (roads, ports, pedestrian and cycle paths, aqueducts, sewers, energy networks, technological and ICT networks, housing, public spaces, etc.).
- The cultural landscape is produced throughout history. It is the heritage (cultural memory) of past generations that must be passed onto future generations as a fundamental element of identity (historic centres, squares and historic buildings, spiritual paths and sacred places, etc.).
- The social landscape is represented by social and civil networks, the density of organisations, the third sector, volunteering, and proximity networks that strengthen relationships, ties and social cohesion.
- The human landscape reflects know-how, skills, knowledge of the territory, local entrepreneurship and the creativity of individuals.
- The economic landscape is made up of local credit institutions, foundations, cooperative banks, third-sector organisations, institutions promoting the financing of neighbourhood projects, and micro-credits.

Following these points, the quality of the complex landscape, and the expression of all its values, has been recognized as the key element of a territorial innovation process that should guide the transformations of the Park, i.e. the entry point for new development dynamics of the territory. In fact, an adaptive and synergistic strategy should not only invest in maintenance, recovery and urban and environmental regeneration, but should also be able to link the various "territorial laboratories" and innovative projects carried out by local communities in the Park, in order to create new symbioses and thus become a source of attraction.

Based on the high potential of the ecological, natural, and cultural resources that characterise the Park, the quality of the space and the functional integration of housing, work, leisure, mobility, social and cultural services, agriculture and natural resources should be improved in order to attract new investments to the area that generate various added values, combining beauty, creativity, knowledge, social environment and economy [9, 10].

In this way, an "economy of places" should be promoted and integrated with the "economy of flows" that currently attracts tourists to the Park for the beauty of its landscape. The integration of both forms of the economy could become a fundamental "strength factor" of the territory, a catalyst for more sustainable economic development [11].

Therefore, a place-based innovation strategy is particularly relevant to enhance the value of places, their identity and diversity, and to give meaning and a role to different

landscapes, stimulating economic growth and endogenous development. The local laboratory system thus becomes an opportunity to build innovative and creative forms of the economy [12], which contribute to enhancing the value of places, regenerating the value chain and at the same time promoting new interactions in ever-new combinations.

The local actors agreed that the National Park of Cilento, Vallo di Diano and Alburni would have to invest in human and social capital to build a more desirable future. In fact, the circular processes that contribute to the creation of resilience and the development of places have a good chance of being implemented only if there is a strong social and human capital.

Indeed, the quality of the landscape, understood as the quality of the places, the infrastructure system, the human and social capital of a territory [13] and the institutions themselves, contributes to increasing or decreasing the productivity level of a territory. For example, a territory's experience and professionalism give it a competitive advantage over other territories, creating an attractive capacity that translates into productivity and wealth.

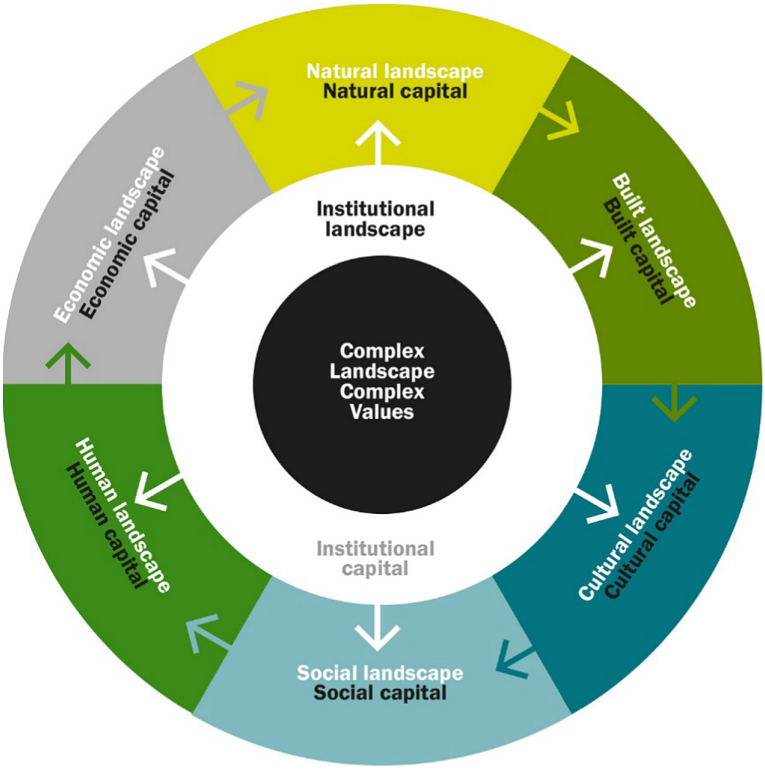

Fig. 1. The six forms of capital and their corresponding landscapes: a synergistic model (Source: adapted from Fusco Girard, 2013)

Therefore, a quality landscape is the result of cultural processes that evolve over time, creating new relationships and knowledge. In turn, the landscape modifies the

territory's knowledge, ideas, and values and, thus, its culture. Talking about knowledge and culture means talking about ideas and values, ways of life, but also about people: their creative and interpretive intelligence, their collective and cooperative capacities, their willingness to forge new common bonds to develop "guiding ideas".

The people who make up the community as a whole have real knowledge, which is different from academic knowledge because it is closely linked to context and everyday life. This knowledge generates the capacity to adapt, experiment, learn and evaluate. High quality human and social capital feeds these virtuous circles.

In the era of globalisation, each territory must identify its own specificities, which make it different and unique, and try to exploit the existence of these differences to be more attractive by virtue of the production factors it possesses and from which its strategic scale can derive locally and globally.

Productivity is closely linked to the ability to activate circular processes. The basis for research into productivity growth and circular processes is research into the use (or re-use) of the knowledge produced in each territory.

Culture is the key factor for local development, and it is, therefore, necessary to invest in strengthening the territorial cultural base as a prerequisite for greater productivity [14]. Culture is the real driver of change and can guide the transformation of the territory towards a polycentric, cooperative organisation, in which critical knowledge allows the choice of the most appropriate priorities for the context, in order to accelerate change and contribute to the construction of a general interest for the territory, making people the builders of the territory and the landscape.

The transition to a human and sustainable landscape requires the participation of institutions and citizens. A bottom-up approach can help to identify a "public space" for dialogue, through which it is possible to build specific responses to the major challenges of our time.

One of the main lessons learnt by the Community of the National Park of Cilento, Vallo di Diano and Alburni is that the identification of a cultural project for the territory and for the landscape is essential for its strategic development, tending towards the "cultural regeneration" of the landscape, open to "shared knowledge" and therefore able to educate to the critical comparison of different values, visions, impacts, in an interactive process open to the different forms of the rationality of the various social actors.

3 Towards Regenerative Landscape Models

The relationship between humans and nature has gradually deteriorated over time. Extracting everything we need from nature has created an unprecedented ecological deficit, and the importance of restoring this fundamental bond is being recognised.

Recent research perspectives focus on the need to rethink how we produce and satisfy our needs, recommending restructuring production processes in a circular modality by analogy with nature. This perspective also introduces a new vision of sustainability, which aims not only at preserving the various forms of existing capital, but also at circularising processes in a more resilient perspective [15]. Resilience is a necessary condition for sustainability because it is related to the ability of a system to adapt while maintaining its own identity under the pressure of external conditions. Synergies and

circularity lead to symbiosis, i.e., an exchange between elements (e.g., the product of one becomes the food of the other) to create stable bonds.

The concept of symbiosis can be compared to that of hybridisation, since both are based on the existence of a dialectical duality (i.e., the existence of pairs of opposites, sometimes in conflict). In reality, hybridisation is not the connection or fusion of heterogeneous (or even incompatible) elements, but rather the deliberate combination of these different entities.

The concept of hybridisation has been borrowed from genetics, where it recalls crossing and grafting, to refer to architectural and urban phenomena, seen as the expression of a living organism characterised by dynamism, complexity, and the capacity for evolution.

Today, the adjective 'hybrid' is used to indicate the intersection between the various components of architecture, urbanism, economics, sociology, but also in the more general field of culture and politics. In fact, the term emphasises the discrepant and contradictory nature of elements that are sometimes deliberately combined, even referring to incompatible logics. The result can therefore be negative, leading to a lack of homogeneity and no concrete results, or positive, because it can generate added value. In this sense, it goes beyond traditional concepts and introduces the need to look at the relationships that have created value over time.

In urban planning, the "hybrid landscape" (urban/rural) concept has been introduced to highlight the coexistence of different organisational structures, natural or artificial, in certain contexts, especially in peripheral areas. The hybrid landscape is characterised by the coexistence of multiple identities.

In architecture, Joseph Fenton has pointed out that hybrid projects express efforts at urban regeneration and the search for greater efficiency in the use of land resources [16].

In economics, hybridisation processes refer to the absence of a clear separation between production and organisational logic. They consist of deliberately bringing together different aspects, characterised by specific organisational architectures, to add value and improve competitiveness. An example is the relationship between profit sectors (companies competing on the market) and non-profit sectors (social enterprises, cooperatives, etc.), which generates a new mutualism and forms of co-production and cooperation, sharing both means and ends. An important example of hybridisation can be found in the service sector, particularly effective in the Living Lab [17–19], where innovative evaluation approaches allow solutions to be defined in a collaborative way, enabling the transition from the experimental phase to the proposal.

In the field of evaluation, the Planning Balance Sheet and the Community Impact Evaluation proposed by Nathaniel Lichfield are tools that express the concept of hybridisation in that they structurally combine the logic of welfare economics (cost-benefit analysis, cost-outcome analysis) with the logic of other approaches (decision theory, governance, etc.) based on the ability to pursue specific objectives.

Multi-criteria, quantitative-qualitative and multi-group evaluation methods are further examples of the implementation of hybridisation in evaluation processes [20].

In the field of culture, hybridisation is structurally related to transdisciplinarity. Transdisciplinary knowledge, as opposed to monodisciplinary, interdisciplinary, multidisciplinary, etc., is based on general systems theory and complexity theory. It has promoted ecological economics, bio-economics, socio-biology, biophysics, art, technology, etc., overcoming the fragmentation of sectoral knowledge and improving mutual relations [21]. Based on the principle of relationality and characterised by a pluralist approach that expands and enhances the current disciplinary perspectives of specialised information, the aim of transdisciplinary knowledge is to "go beyond", i.e., to transcend disciplinary approaches, to identify new approaches, new models, and perhaps even new paradigms.

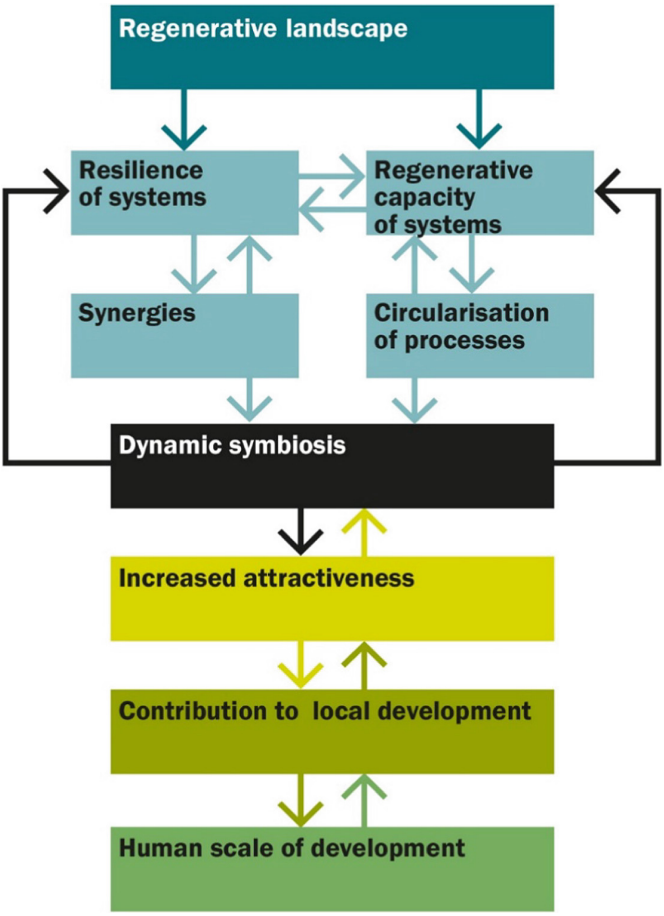

Fig. 2. A model for the development of a regenerative landscape

Transdisciplinary research is characterised by a high degree of integration, not only in terms of research between technical and professional disciplines, but also between problem-solving and learning skills, between academic and non-academic knowledge,

and between theoretical and operational knowledge. From this approach, landscape is a good example of a research area that requires a structurally transdisciplinary approach.

In this perspective, we propose the landscape regeneration development model shown in Fig. 2. It describes synergies' key role and processes' circular organisation in improving landscape resilience. In fact, the links and relationships between the different forms of capital generate development activities. More specifically, the density of these links and relationships generates capacities, values, work and employment, and thus new opportunities for human development. The model, therefore, uses synergies, circularity and symbiosis as tools for multiplication. Extended to the urban and social context, the circularity of processes can be transferred from industry to the organisation of the city and territory itself, to the economy, to the social system and to governance [8, 22].

As defined by Chertow [23], industrial symbiosis is an activity that involves normally separate industries in a collective approach to competitive advantage, including the physical exchange of materials, energy, water and/or by-products. The key to industrial symbiosis is cooperation and the synergy opportunities offered by geographical proximity. Industrial symbiosis is part of the broader field of industrial ecology (from which it is a direct application) [24], which, by optimising material cycles, has implications for planning, environmental management, and economic development.

An extension of industrial symbiosis is urban symbiosis, an activity that transforms solid waste into inputs for the industry. It was introduced by van Berkel et al. [25] to describe recycling activities that find their reason to be in the geographical proximity and synergistic relationship between solid waste producers and industries.

The concept of urban symbiosis is closely linked to "the use of by-products (waste) from cities (or urban areas) as alternative raw materials or energy sources in industrial operations", resulting in the reduction of pollutant emissions and the recovery of raw materials. New symbiotic opportunities are created by creating a link between solid waste and local industry.

This cyclicity is reminiscent of natural ecosystem processes. Another symbiosis is that between urban and suburban areas [26]. The benefits of synergetic, symbiotic, and circular processes are expressed not only in lower environmental costs, but also in the generation of greater economic benefits and new jobs. They, therefore, contribute to determining the specific attractiveness of an area compared to others. In essence, these processes shape the urban and suburban landscape: they make it more or less attractive for the location of new activities, new investments, and specialised manpower.

Based on the territorial relations system, this local economy model is more resistant to the globalized economy's shocks and offers greater opportunities for self-government and self-sustainability. It identifies the different circuits of value creation (cultural, economic, and civil), which are put in synergy with each other based on the principle of relationality between economic productivity, manufactured and infrastructural capital, cultural heritage, social capital, environmental/natural capital, and human capital/creativity.

4 Conclusions

Cities and territories are increasingly investing in the knowledge economy, redirecting financial resources to stimulate investment in the production of knowledge. Culture is not only ideas, but also values, and ways of life that shape the landscape. The production of knowledge can help decision-makers balance objectives of economic efficiency with objectives of social cohesion and environmental sustainability.

The real challenge for the future is the ability to promote a new "science for the city and for the landscape" with a more forward-looking approach: the ability to build an integrated transdisciplinary, holistic and, at the same time, more operational approach, based not only on academic but also on technical-professional expertise, towards a post-disciplinary perspective.

Possible perspectives for new research on landscape and territory to promote the transition to a new circular economy should concern some important themes: the role of intangible capital for the production of wealth in cities and territories; the construction of symbiotic, metabolic and hybrid processes; the identification of new management models to improve living conditions; the implementation of good practices using specific evaluation tools; the multidimensional evaluation of territorial impacts; finance and sustainable development; entrepreneurship and eco-innovation; entrepreneurship and the social economy [27].

The key element in all of the above themes is the recognition of the role of culture in making the landscape more desirable for the future, where circular economy processes can contribute to a series of benefits in terms of reducing costs and waste, creating new jobs, reducing environmental impact and activating transition processes towards a new development model based on the interpretation of land and landscape as a living organism, regenerating co-evolutionary and cultural relationships.

As demonstrated by the territorial laboratories activated in the Cilento Labscape project, the interaction between skills and knowledge provides complementary views and interpretative approaches capable of activating new synergies. In fact, each laboratory, although focused on different themes, has made it possible to interpret the territory and to identify with the local communities the opportunities for networking values, interests and resources. Through the different interpretations of the landscapes of the National Park of Cilento, Vallo di Diano and Alburni, it was, therefore, possible to imagine a new geography of the Park with the local actors, pioneers of territorial innovation processes.

A common element of each laboratory was the concept of the "regenerative landscape", according to which the landscape, as a collective resource, requires an organisational structure that encourages the choice of individual cooperative strategies that consider the impact of one's own actions and decisions on the environment and on the other beneficiaries of the landscape.

In this context, it is important to recognise that, through a dynamic participatory process, the local communities are able to give themselves organisational structures that are attentive to dynamic change and adaptable to the transformations suggested by the emergence of new knowledge.

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An Evaluation Methodology to Support the Definition of Temporal Priorities Lists for Urban Redevelopment Projects

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Abstract. The present research concerns the relevant and current issue of the urban regeneration. In particular, a methodological approach for the identification of the areas - included in a city district or a larger macro-area - for which a higher urgency of urban redevelopment is detected, is developed. The proposed methodology intends to support the definition of the temporal priorities and preference lists of the interventions to be implemented in a territory, providing an evaluation tool able to highlight the areas on which the first attention of public decision-makers should be paid, in order to start urban transformation initiatives on a larger scale. The articulation of the methodology into 7 phases is illustrated and its flexibility of implementation is pointed out, to allow the replication of its operational procedure in every geographical context and for different intended uses. The methodology constitutes a valid reference for public decision-makers involved in the definition of programmatic guidelines for urban regeneration and of specific targets for the urban development policies.

Keywords: redevelopment projects · temporal priorities lists · urban policies · sustainable development goals · property prices · influencing factors · real estate market

1 Introduction

The need of planning interventions to be carried out on the urban territory, according to targeted strategic lines, is increasingly central, due to the reduced spending capacity of Public Administrations and, at the same time, the precious opportunity provided by European funds (Next Generation EU [1], National Recovery and Resilience Plan (NRRP) [2], Cohesion Funds [3–5], etc.).

In this sense, the evaluation constitutes a fundamental support for investment choices, first of all by highlighting the greater or lesser urgency of operating in a territory and, subsequently, by allowing the verification of the financial sustainability (in the case of public private partnerships) and the economic feasibility of the initiatives.

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Starting from an extended urban macro-area (district, suburb, etc.) characterized by a widespread state of degradation, the urban regeneration processes envisage the definition of an integrated approach capable of revitalizing entire city portions. This approach should consider the different zones included in the macro-area in which a greater urgency for intervention is detected and which could become pioneers of large-scale urban renewal and growth phenomena.

The lists of temporal priorities and preferences of the interventions to be implemented are part of this issue, aimed of defining a program plan of the operations to be carried out, with a common purpose of the strategic vision for the development of the areas that, from punctual and targeted initiatives, may reach a global improvement of the cities.

In this context, in the recent decades the European Union (EU) has promoted an in-depth debate on cities and their development, by determining an "EU perspective" on the topic called "urban acquis" since the end of the 1990s [6]. Already with the co-municipal initiatives URBAN I 1994–1999 and URBAN II 2000–2006 [7–9], the focus has been placed on an integrated approach able to associate the promotion of the economic activities with the improvement of infrastructures and the environment, the provision of customized training to the actions in favor of equal opportunities and the adaptation of social services.

The main European funds used to carry out the urban regeneration interventions included in these programs are the European Regional Development Fund (ERDF) [10] and the European Social Fund (ESF) [11], integrated with national and local funding.

In 2007, the Leipzig Charter [12] recommends a greater use of integrated urban development policy strategies in which the specific spatial and temporal aspects of the most important urban policy sectors should be coordinated. In this sense, each government should i) identify the main strengths and weaknesses of the city and the neighborhoods based on the current situation analysis, ii) define concrete goals for the urban areas development and iii) coordinate the projects related to the different neighborhoods, in order to ensure a balanced territory development, by orienting the effective use of funds by public and private sectors.

Furthermore, the urban planning tools must be connected at the local and metropolitan region level and involve the communities who can contribute to determining the future economic, social, cultural and environmental quality of each area. The application of a holistic and integrated development policy constitutes the key principle for the definition of a sustainable urban development that overcomes a purely sectoral policy and is supported by multi-level and stakeholder cooperation, by pushing the administrative boundaries. Following the success of the URBAN initiatives, the sustainable urban development policies have been fully included into EU funding mechanisms and have become central to Cohesion Policy (2007–2014). Subsequently, during the 2014–2020 programming period, among the Cohesion Policy objectives, the promotion of integrated urban strategies with the aim of strengthening the role of cities has been highlighted. Thus, the ERDF supports the sustainable urban development through integrated strategies to address the economic, environmental, climatic and social challenges of urban areas (art. 7, par. 1 of the regulation proposal of the European Parliament and of the Council on specific provisions concerning the European Regional Development Fund and the Investment for growth and jobs goal and which repeals Regulation (EC) No.

1080/2006 [13]). In this context, the Cohesion Policy has established that at least 5% of the ERDF resources allocated to each EU Member State are invested in integrated actions for sustainable urban development. New territorial tools have been also defined for the implementation of strategies in urban areas, in particular the Integrated Territorial Investment (ITI) and Community-Led Local Development (CLLD). In the current Cohesion Policy 2021–2027, it has been proposed to increase by up to 6% the minimum ERDF contribution to the urban sustainable development. The promotion of urban areas transformation policies will take place through a place-based approach to development, based on the multi-sectoral and multi-level governance with the participation of a plurality of stakeholders, and a participatory-type strategy that will concern multiple territories.

2 Aim

Within the sustainable urban development goals, the planning modes of effective strategies by Public Administrations are not unique, having to adapt to the specificities of the territories and the needs of the communities. Furthermore, the adequate management of the funding allocated on a regional and national scales for urban regeneration interventions is fundamental in order to achieve the goals set by the Agenda 2030 [14] and to create resilient cities. In this sense, the strategic planning should be intended as a flexible process capable of managing the changes and the populations' needs. Therefore, the urban policies should combine the issues of the physical space quality with those of territorial enhancement, social cohesion and economic revitalization, through a programmatic approach linked to defined times and to the technical and economic-financial sustainability of each interventions. In the outlined framework, given an urban macro-area to be redeveloped, the present research intends to develop a methodological approach for the identification of the areas for which a greater urgency for transformation is detected [15]. The proposed methodology aims to support the definition of the temporal priorities and preference lists of the interventions to be implemented, in order to guide the selection phases of the urban regeneration initiatives and to plan future ones. While promoting the preservation of the unitary character of the urban transformation initiative, the research intends to provide an evaluation tool that highlights the areas on which the first attention of public decision-makers should be paid, in order to start urban redevelopment initiatives on a larger scale.

In general terms, the study of the real estate market reveals the preferences shown by buyers and sellers within a specific spatial and temporal horizon. In fact, the selling price represents a synthetic indicator of potential buyers' willingness to pay and current owners' willingness to sell, based on the main intrinsic factors of the properties and the overall quality level of the urban context in which the asset is included. Therefore, since the property value is the result of a complex of intrinsic and extrinsic factors, it is assumed that a variation in the conditions that characterize the area determines an impact on the market value. Using the Hedonic Price Model, the total selling price of the property can be broken down into different components relating to the various intrinsic and extrinsic characteristics that are influential in the price formation process. Taking into account this aspect, an increase or decrease observed for the extrinsic variables

leads to a change in the property price connected to them. The logic underlying the proposed methodological approach concerns the existing relationship between the real estate prices and this category of variables, by assuming the property asset price increase as a proxy of the benefits generated by the urban redevelopment intervention for local communities.

The methodology is structured in different phases which, starting from the detection of the main potentially attractive landmarks or poles in the area (public spaces, historical, landscape and artistic assets, road and public transport infrastructures, health, school, cultural and religious facilities and buildings, etc.), through the implementation of an econometric technique, allows to identify the main places of the area considered by the local market as positive factors (key good elements) or negative ones (bad elements). The identification of the urban poles whose proximity is a determinant scarcely appreciated by the potential buyers of a real estate property implies the detection of the areas for which a greater urgency of intervention in terms of time or entity is found. On the contrary, cultural, architectural, landscape, etc. emergencies whose proximity to the existing building stock represents a positively appreciated market factor, are those that do not require punctual redevelopment, but which could be included in broader urban renewal policies.

The methodological approach intends to guide the decision-making processes of public entities for the definition of a strategic framework of territorial sustainable development initiatives and of private investors in the situations of public-private partnership to orient them towards choices that are financially profitable. In fact, if for the local governments the analysis carried out constitutes a valid support tool for urban dynamics, for private subjects, the developed methodology allows to identify the areas in which the investment is more convenient, in line with the current market appreciation and the likely variations as a result of urban regeneration interventions.

The Sections contents included in the paper are described below: in Sect. 3 the issue related to the importance to carry out an integrated approach for the urban regeneration decisions is highlighted. In Sect. 4 the proposed methodology is illustrated and the main steps that constitute the logical procedure to be implemented in order to identify the areas to pay attention for urban regeneration are described. In Sect. 5 the conclusions are introduced and the further insights of the research are listed.

3 The Collaborative Approach in the Urban Regeneration Decision Processes

To effectively improve the cities development prospects, the strategic planning requires integrated processes of collaboration between the different subjects involved in the initiatives in a multi-level governance system that includes the beneficiaries of the policies, i.e. the citizens, the businesses, the associations and the political decision-makers.

The definition of urban regeneration scenarios characterized by an inclusive "citizens centred" [16] approach is very often encouraged for adequate choice processes implementation. In this sense, the involvement of the local community with needs, requests and aspirations in the decision-making mechanisms is strongly requested by the governments. The modalities of participation in the public political debate aim to promote

local inclusion practices in order to combine the urban planning choices with the current community demands. The main goal is to favour the involvement of an active dialogue to develop shared "agreement" between the population, the professional and the academic communities. In the reference literature, numerous researches focused on the progressive prominence of the citizen participation in governance networks oriented towards urban regeneration can be detected [17–22].

In the current context, it is evident the complex nature of the urban transformation projects, mainly due to the different involved stakeholders, such as the local and central governments, the private developers and the local communities. These subjects often dissimilarly intend to implement the regeneration strategies as they assign different weights on the environment, housing, social welfare, and commercial enterprises [23, 24], in relation to the own interests and roles. In theoretical terms, the collaborative processes aim to provide a decision-making process able to obtain effective outcomes by which all stakeholders could maximize their benefits by exchanging information [25]. The existing scientific studies have attempted to analyse the relationships between the various stakeholders and to investigate the coordination mechanism of their interests by using several approaches and tools within different contexts.

However, the variability of stakeholders' interests strongly linked to the macro-economic changes and the expressed needs of the community makes it impossible to define a single approach of collaboration between governments and communities, but this should be tailored determined on the basis of the specificities of the geographical context, the physical, socio-economic, cultural and environmental conditions of the site to be redeveloped and of the current and forecast market supply and demand. It should also be pointed out that the community participation, especially in developing countries [26] in which the awareness of the citizens is often low, should be developed taking into account the political, social and economic situation of each involved subject [27–31], i.e. the individual's living environment, the economic status, the educational level that potentially influence the people's participation [32, 33]. In the framework outlined, the growing importance given to the collaboration integrated approaches between governments and stakeholders in the local public policies development has transformed the public *modus operandi* from the "static" governance of the urban transformation dynamics in which the different actors acted in solitary form due to their conflicting interests, to a "dynamic" governance, i.e. in terms of a collective process aimed at the definition and management of policy-making in which the interactions and different forms of partnership between the different stakeholders are defined.

4 Methodology

The methodology proposed in the present research aims at identifying the areas included in a larger urban macro-area (district, suburb, etc.) for which a greater urgency for transformation is detected.

The methodology is structured in 7 phases:

- the first step concerns the identification of the main landmarks (architectural, historical and environmental emergencies) included in the considered urban macro-area. These poles should be selected regardless of their current maintenance conditions,

i.e. by considering the existing or potential attractiveness they could have due to their localization and function. In this sense, the chosen landmarks could constitute amenities (whose proximity is positively appreciated on the reference market) or disamenities (whose proximity negatively affects the choices of buyers and sellers) of the analyzed urban territory;

- the second phase regards the detection of the main intrinsic factors that ordinarily influence the choices of buyers and sellers in the specific market segment analyzed (residential, commercial, management, etc.). These characteristics are selected by consulting the main operators of the local real estate market and evaluating the main positional, technical-typological and juridical-economic significant aspects in the buying and selling phases;
- the third stage aims at collecting a sample of properties (residential, commercial, office, etc. according to the purpose) sufficiently representative of the local real estate dynamics, recently sold, with known selling prices and characteristics. For each individual included in the study sample, the values of the mentioned selected intrinsic variables and those of the extrinsic variables in terms of distance from each considered landmark are recorded;
- the fourth step focuses on the implementation of an econometric technique for determining the most influential intrinsic and extrinsic factors on selling prices. In particular, the technique allows to obtain a large set of models expressed in polynomial form for which the selling price is function of a set of variables among those initially analysed, multiplied by numerical coefficients and raised to the proper numerical exponents [34, 35];
- among the different models generated by the polynomial regression model, in the fifth step the selection of that i) characterized by an adequate statistical performance level, ii) with an algebraic not excessively complex expression, iii) best interprets the specific real estate dynamics of the analyzed context, is carried out. Having chosen a model on the basis of i) and ii), the verification of the empirical consistence of the coefficient's signs should be performed, by taking into account the variation of the i-th variable analyzed in the interval of the observed sample and keeping the values of the other variables constant and equal to the respective average value;
- the sixth phase intends to analyze the functional correlations between the variables selected by the model and the selling prices in order to assess the positive or negative appreciation of the market for each factor. Furthermore, the marginal contributions given by the intrinsic and extrinsic variables (expressed in terms of distance between each property in the sample and each considered landmark) on prices are determined. By taking into account the main goal of the developed methodology, in this phase, among the urban poles initially considered in the analysis, those for which the greatest impact on the selling prices formation processes are highlighted, are identified;
- in addition, among the landmarks included in the chosen polynomial regression model, in the seventh phase those whose proximity negatively affects the choices of buyers and sellers are pointed out and, therefore, the areas for which a higher attention from public entities should be paid are focused. The outputs obtained in terms

of scarce/non-appreciation by the reference market for specific landmarks allow to identify the areas for which a greater transformation cogency is detected.

Figure 1 shows the listed and described steps in a flowchart in which each phase is preparatory to carrying out the next one, in line with the overall aim of defining the temporal priorities lists for urban redevelopment projects.

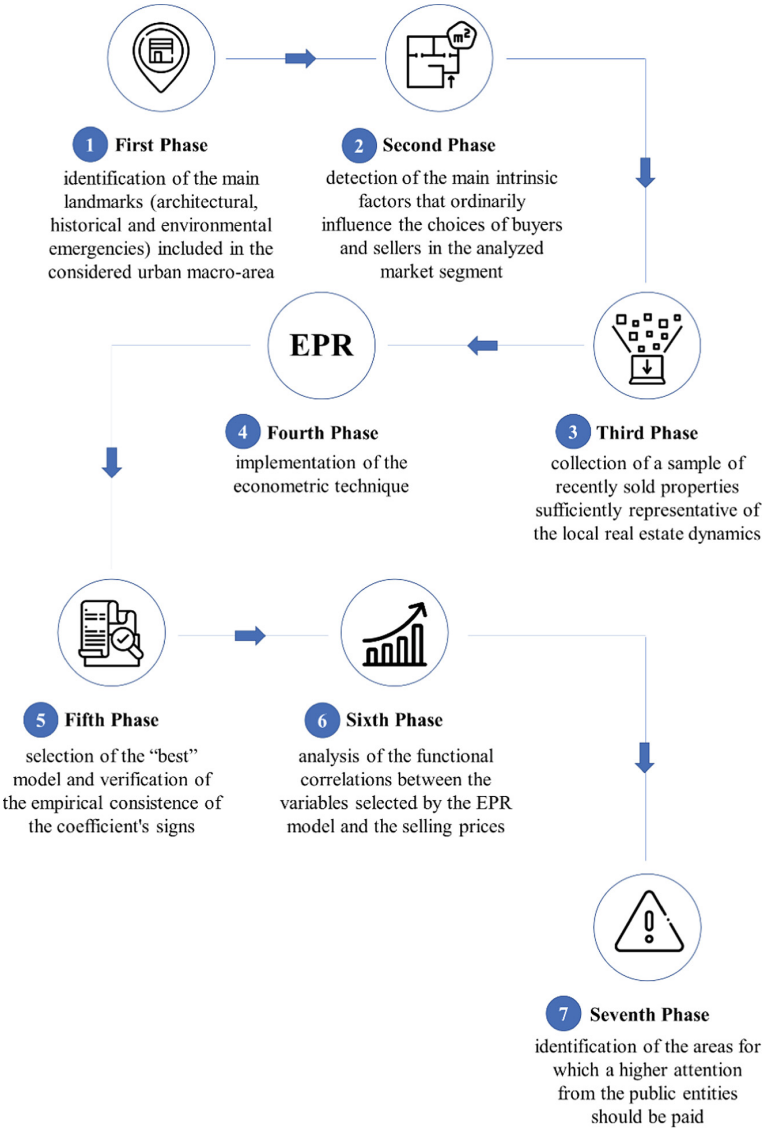

Fig. 1. The 7 phases of the proposed evaluation methodology

The developed methodology constitutes an evaluation tool to support the decision-makers in the development of effective strategic urban regeneration processes, through the preliminary identification of the areas to be included in the temporal priority lists among the most urgent projects to be implemented. The proposed approach borrows the logic according to which a variation in the maintenance conditions of a historical, architectural or environmental emergency affects the general level of urban quality of the area in which this emergency is located and, consequently, has an impact on the value of the existing building stock and on the preferences of potential buyers in the context of purchase and investment initiatives. Therefore, the cascade system links the different mechanisms of the reference market to the effects connected to the urban regeneration intervention, in terms of increasing the level of urban quality of the area in which the intervention is included and, more generally, of improvement of the community quality of life.

Figure 2 reports the relationship between the urban transformation intervention, the increase in urban quality of the area in which the project is implemented and the positive variation in real estate values. The direct relationship that associates the raising of the quality conditions of the place, consequent to any redevelopment intervention on an urban scale, and the increase in the values of the urban property stock represents a relevant assumption of the proposed methodological approach.

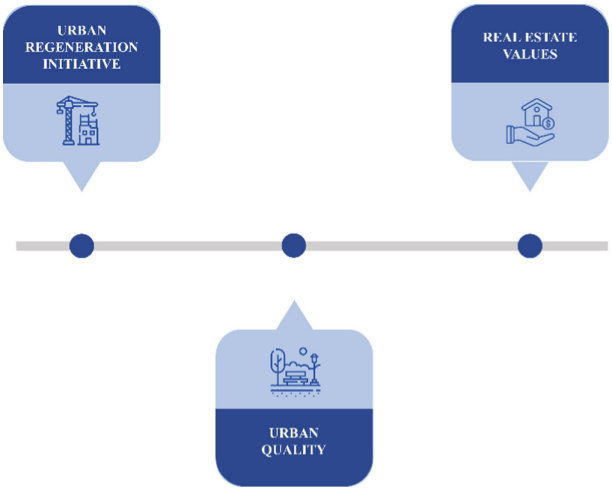

Fig. 2. The relationship between the urban regeneration initiative, the urban quality and the real estate values.

It should be highlighted that, for the development of the methodology, the influence of different external factors which overcome the two-way relationship related to the increase in urban quality and the growth in real estate values, and could modify the expected final outcome of a transformation intervention in terms of effects on the urban system, has been neglected.

First of all, among these factors, the consequences of the economic-financial crisis of the main European countries, whose effects add up to those determined by an urban transformation, should be mentioned. In fact, the impacts of the project implementation on the selling prices could be interpreted as an attenuation of the phenomenon of the decrease in real estate values caused by the crisis in the real estate market.

Likewise, any collateral effects deriving from the implementation of an urban regeneration intervention which, if not effectively planned in all its aspects, could occur in terms of changes in the structural dynamics of the real estate market, have been omitted. For example, in theoretical terms the consequences associated with a project for the pedestrianization of an urban area concern the creation of new spaces for aggregation but, also, the vehicular traffic flows shift to alternative road arteries.

The succession of the phases in which the proposed methodology is articulated, has been implemented with reference to an urban macro-area to be regenerated located in a municipality in Southern Italy and to the residential market segment.

In Fig. 3 the localization of the considered macro-area within the urban context of the considered city is reported.



Fig. 3. Localization of the macro-area to be redeveloped in the urban context

Given the need to renovate the analysed macro-area, due to its spread decay conditions, the analysis has been developed starting from the identification of the main landmarks located in the city portion (architectural, historical and environmental emergencies) (first phase).

In Fig. 4 the landmarks included in the macro-area and selected for the analysis are shown.

Moreover, the detection of the main intrinsic factors influencing the choices of buyers and sellers has been performed in the second phase. In particular, in the research the main real estate agents whose expertise area concerns the analyzed macro-area have



Fig. 4. Landmarks selected for the analysis

been consulted in order to choose the factors that mainly influence the current processes of formation of selling prices in the specific market area.

In Table 1 the intrinsic factors considered in the analysis are reported.

Table 1. Intrinsic factors considered in the analysis

Intrinsic Factors	Type of Variable	Measure
Floor surface	cardinal	m^2
Number of bathrooms	cardinal	number
Floor level	cardinal	number
Presence of lift	dummy	1 = presence, 0 = absence
Quality of the maintenance conditions of the property	dummy	1 = category that defines the specific quality of each property, 0 = the remaining two categories
Energy label [A-G] of the property	dummy	1 = energy label of the property, 0 = all the others
Age of the building	cardinal	number = difference between the year of sale and the construction year of the building

Furthermore, the third step of the proposed evaluation methodology has concerned the collection of a study sample consisting of three hundred residential properties sold between March and December 2021. Therefore, for each property the total selling price,

the distance from each landmark specified in the first phase (expressed in km to walk to it) and the values of the intrinsic factors, have been quantified.

In order to compare the data, the values of each variable have been normalized by the maximum value found for each category, so that a unique range of variation between 0 and 1 has been considered. In this sense, a database has been structured and some statistical analysis have been carried out to check the consistence and reliability of the sample and to identify any anomalous data to be removed.

The localization of the properties within the analyzed macro-area is shown in the Fig. 5.



Fig. 5. Localization of the residential properties detected for the study sample

In the fourth step of the assessment methodology, an econometric technique has been implemented in order to obtain a wide set of polynomial equations composed by different additive terms in which some or all of the initially detected explanatory variables are multiplied by numerical coefficients and raised to exponents. Starting from these models, the determination of the most influential intrinsic and extrinsic factors on the price formation processes has been carried out and the explanation of the functional correlations between the prices and the factors selected by the technique among those initially considered has been performed.

Among the different generated models, the best one, in terms of statistical performance, complexity of the algebraic form and empirical consistence of the coefficient's signs included in the mathematical expression, has been chosen in the fifth phase.

For each factor (intrinsic and extrinsic) included in the selected model, the analysis of the functional links (direct or inverse) between the explanatory variables and the selling prices has been carried out. Through this operation the evaluation of the positive or negative appreciation of the market for each factor and, with reference to the aim of the research, the explanation of the marginal contribution provided by the extrinsic

variables (expressed in terms of distance between each property of the sample and each considered landmark) on property prices, have been developed.

Some of the main functional relationships that could be obtained between each variable and the selling prices are reported in Fig. 6. It should be highlighted that, for the extrinsic variables, a direct link indicates an increase in property prices as the distance from the analyzed landmark grows. This situation points out a scarce appreciation by potential buyers for the proximity to the specific urban pole, which is reflected in a reduction in the selling prices of the proprieties overlooking/very close compared to those found for properties located in more distant urban areas.

On the contrary, an inverse functional correlation between the distance of the properties from the landmark and the real estate prices highlights this pole as a factor whose proximity is appreciated by the local market.

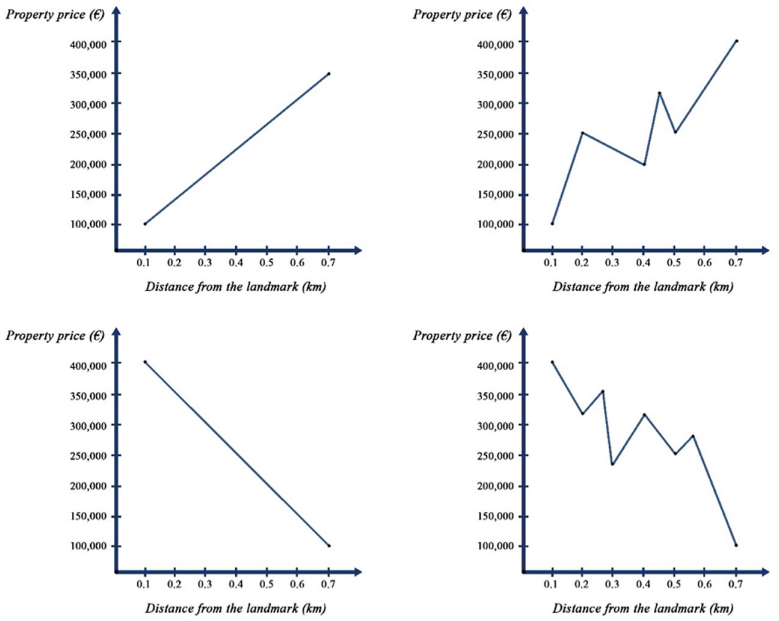

Fig. 6. Main functional correlations between selling prices and each selected explanatory variable

The different trends analysis has allowed in the seventh phase to detect the landmarks whose proximity negatively affects the selling prices and, consequently, the urban areas included in the macro-area for which a higher attention from public entities should be paid.

Figure 7 reports a summary of the outputs obtained in terms of positive (green dot) and negative influence (red dot) of the locational extrinsic variables selected by the polynomial regression model on property prices. The yellow dots indicate the landmark for which a limited market positive or negative appreciation has been detected. The graphic representation constitutes a useful support reference within the decision-making processes related to the definition of the temporal priority lists of urban regeneration

interventions as it is immediately readable in the programming and planning phases of the territorial initiatives to be implemented.



Fig. 7. Outputs obtained in terms of positive (green dot), negative (red dot) and "negligible" (yellow dot) influence of the locational extrinsic variables selected by the polynomial regression model on property prices. (Color figure online)

5 Conclusions

During the last decades, the urban regeneration constitutes a strongly discussed topic in the scientific literature and in the political debate [36–41]. Starting from a narrow conception of the recovery and redevelopment of the existing property assets and the urban spaces, over time the question of urban regeneration has involved environmental, social and economic aspects. In this sense, the urban transformation initiatives aim at improving the quality level of the area in which the intervention is located and, more generally, of the city. Furthermore, the direct involvement of the communities in the urban interventions planning plays a central role in the choices processes, as it is fundamental to begin by defining the current needs framework in order to activate valid initiatives able to improve the life quality of the citizens, in coherence with the set sustainable development goals.

Within the public policies aimed at defining effective projects to be implemented on the territory, in the present research an evaluation methodology has been developed to support the stages related to the definition of the temporal priority lists of the interventions. After verifying the urgency of redevelopment in a city portion characterized by a widespread state of degradation, caused by the presence of inadequate infrastructures, abandoned buildings and/or underused public spaces, the definition of appropriate valid

planning strategies represents an essential operation for conscious and successful urban initiatives.

In these situations, the projects assessment discipline assumes a crucial importance, allowing to orient the decisions processes towards the most urgent investments. The methodology proposed in this research is part of the support tools to be used for temporal priorities lists of urban redevelopment projects definition, i.e. in the preliminary design stages.

The 7 steps into which the developed methodology is articulated allow to identify the areas for which a greater need of intervention is observed, given the current scarce or lacking appreciation of the market for the proximity to specific city landmarks. The methodology constitutes a valid reference for public decision-makers involved in the definition of programmatic guidelines for urban regeneration. The methodology's implementation flexibility allows to replicate its operational procedure in every geographical context and for different intended uses, to verify the influence of the areas to be redeveloped on the property values and to define specific targets for the local development policies.

In accordance with the always increasing relevance of the urban regeneration issue in the strategic programs developed by central governments, connected to the sustainability goals fixed by the Agenda 2030, the present research is consistent with the current need of providing the local governors of effective tools to guide the urban planning and design, in order to improve the quality of the existing building stock and public spaces and to increase the life quality of the communities. The identification of the most critical urban areas constitutes a useful support in the investment choices of private and public operators.

Future developments of the research will concern the implementation of the proposed methodology with reference to a specific case study in order to test the validity and reliability of the developed approach. In this sense, the application of the methodology can be included in the first phases of the selection of the projects to be realized, in line with the main goals of the urban policies to be carried out. Therefore, after having identified the most critical areas that should be included in the temporal priority lists among the most urgent interventions, the methodology can integrate the overall analysis of an urban context aimed at identifying its strengths and weaknesses, to guide the initiatives towards strategies consistent with the needs of the community that are reflected in the property purchase decisions. The practical outcome of the methodology application could be a map in which the most critical urban areas are highlighted, in order to immediately visualize the results of the analysis and to provide a useful support in the investment choices of private and public operators. In particular, the map could orient the private operators in their investment decisions, through a higher awareness of the current and forecast market appreciation, whereas, for the Public Administrations, the map will be a reference for the calibration of the urban regeneration policies, in order to eliminate or, at least, reduce the existing gaps between the different parts of the city.

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The Strategic Planning for the Promotion of Cultural Tourism in a Wide Area of Calabria: The Armeni Valley

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Abstract. The study, second phase of an applied research on a wide area of the Metropolitan City of Reggio Calabria, aims to identify, within the framework of strategic planning, the best actions for the enhancement of the tourist-cultural offer of specific territorial contexts, such as inner areas. The contribution reports some reflections on the evaluation tools suitable for the selection of strategies and the related actions to favor changes of strategic-cultural value and the triggering of an intelligent, sustainable and inclusive development of the territories. In the hypotheses proposed, actions and tools converge capable of borrowing the methodology of strategic planning by applying it in a sectoral way to Cultural Heritage.

Keywords: Strategic Planning · Economic-Estimative Evaluations · Cultural Heritage · Inner Areas · Local Development · Cultural Tourism

1 Introduction

The paper illustrates the methodological approach and the first application results of a research activity conducted by the UNESCO Med Lab of the Mediterranea University on a wide area of the Metropolitan City of Reggio Calabria on the following topics:

- Strategic Planning focused on Cultural Heritage as a tool for the development of specific territories, such as inner areas;
- the contribution of economic-estimative evaluations to the selection of actions and to the identification of the most suitable tools for estimating the impacts.

The study introduces a path of strategic planning of a wide area focused on the valorization of cultural heritage (material and immaterial), useful not only for political decision-makers but also for local communities, for a better identification and solution of problems.

The research proposes some actions and tools capable of transforming territorial planning into "cultural planning of the territory", and of expressing a multi-development, locally based and competitive on the market since it is woven on the specific evolution of places. The proposed strategy converges in the direction of attributing a strategic value

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to the territorial quality and cultural identities of local contexts, of interpreting them as resources to be known, interpreted, conserved, valued and communicated.

The case of the Armeni Valley in Calabria (IT) is analyzed, identifying the features of the strategic planning at the basis of the revitalization of the territory. It is an ongoing process that cannot be separated from a research question that focuses on identifying the optimal strategies closely related to resources, for the revitalization of local economies.

The paper illustrates the methodological approach and the results of the first activities already carried out on the case study.

2 Strategic Planning: State of the Art

Strategic planning for territorial development is one of the topics on which the sector literature has paid the most attention in recent years. The basic idea is that at the local level it is necessary to read the territory, select sustainable intervention priorities and guide public and private resources around these, building a shared vision and a path that takes into account the general interest of the community [1].

On this bases, strategic planning is understood as the process that mobilizes a plurality of subjects in the reconstruction of a territory "vision of the future" starting from the representations expressed by the local actors who contribute to redefine its identity; it is a framework which, describing the goal and outlines strategies, actions and tools to achieve it [2]. It is also an action of continuous verification and monitoring of results and of reviewing actions according to the changes that can affect the local or extra-local context [3].

The construction of territorial policies based on strategic paradigms has become established at all levels of planning. But, while at the level of the municipal and implementation plan the regulatory aspects retain their prescriptive importance, at the supra-municipal level strategic planning has become increasingly incisive [4]. In fact, the concept of territory has recently undergone a radical transformation: from a material resource susceptible to exploitation, a controllable space where diversity is seen as resistance to transformation, we have come to an interpretation in which the relational and uncertain characteristic of a complex system. Consequently, planning requires new approaches: the challenge of complexity can be successfully addressed through a greater conception of multiple and intelligible responses [5].

In recent years, with reference to the dynamic and procedural nature of the Strategic Plan, it has been underlined how the latter lends itself well to processes of continuous innovation, both as regards the theoretical-methodological reflection and the implementation phase [6]; on the other hand, referring to urban and territorial contexts that are also very different from each other, it is highly heterogeneous in terms of content and design. Despite, a substantial homogeneity of objectives, aims and methodologies emerges with equal clarity [7].

In relation to the other territorial regulatory tools, the new 2030 Agenda proposes pursuing sustainable development objectives in the EU territory by leveraging the resilience capacity (circular economy, green economy), as a methodology for dealing with the new economic, social and environmental, but above all as a tool to create employment and lasting development without altering the territorial characteristics.

This territorial development model can also be adapted to Italian inner areas, mostly concentrated in the South [8]; areas that have represented in the past a point of reference for large segments of the population and whose crisis appears as an alteration of the network of relationships between the economic and social structures [9]. Indeed, it is known how much the latter need to revitalize their economies, as well as demographic structures, through diversified actions based on processes of regeneration and self-sufficiency [10, 11].

Because of that, the Strategic Plan can constitute a tool which contrasts the ongoing centralization of decision-making with the practice of comparison and polycentrism on an inter-municipal basis with the objective of sustainable development of local economies [12].

It is in these contexts that interesting reasoning related to a "cultural planning of the territory" can be conducted. For some years it has been addressed in a large part of Europe no longer as a sector or as a simple qualitative attribute of development, but as the matrix of all development sustainability: constitutional, cultural, managerial and economic sustainability, considered as fields of opportunity for the protection and enhancement of the cultural fabric of places [13]. What has been investigated is the dual role of the cultural framework of the territory as a matrix of the identity of places and as a strategic and priority line of local development, starting from some fixed points of a renewed declination of sustainable development: the whole territory is seen as a cultural system, as the result of processes stratified over time and as a creative opportunity for new interpretations, compatible interventions and economic values put by history and culture on the table of competition [14].

To date, this approach is finding a decisive and new impetus also in Italy; in recent years, the attention given by national institutions and ministries has transformed into a progressive development project for the country, which has found a moment of strong convergence in the Piano di Sviluppo Turistico 2017–22 - *Italia paese per viaggiator*i, which declines the theme of sustainability by making cultural heritage a development tool [15].

Strategic actions based on these assumptions can give life to local growth processes capable of combining economic-employment development with the protection and enhancement of the heritage, the environment and typical products, producing widespread and non-selective effects and guaranteeing visibility to smaller territories that is perceivable by potential visitors and investors.

3 Methodology

The study, second phase of an applied research on a wide area of the Metropolitan City of Reggio Calabria, intends to offer an innovative framework in the Strategic Planning of a wide area focused on the enhancement of the Cultural Heritage of specific contexts subject to phenomena of marginalization, such as inner areas; objective is the promotion of sustainable and quality tourism based on endogenous resources for the development of territories with unexpressed cultural potential.

The research analyses the proactive function of valorization, conservation and reuse of cultural heritage in the planning process. The main objective is to identify and evaluate the existence of conditions that demonstrate the function of cultural heritage and cultural production as a driver of strategic regeneration of territories.

The contribution intends to provide guidance on how to set up an effective strategic planning process, which derives from a process of rethinking and relaunching territories; a reflection on the possible evolutions of planning is proposed, and then a strategic choice process is introduced, whose procedural, interactive and flexible character allows to overcome some limits of traditional planning, deriving from a linear and hierarchical vision, setting up a holistic vision and a parallel character of specificity of the interventions aimed at particular problems, thus overcoming the opposition between plan and project.

Therefore, the application of this process in the Armeni Valley in Calabria (IT) is proposed, as a test bed to experiment with the themes outlined above.

The study also introduces the first reasoning on the identification of the most appropriate evaluation techniques for the selection of strategic actions, useful not only for political decision-makers but also for local communities, for a better identification and solution of problems.

The methodology followed includes four distinct phases (see Fig. 1):

– Phase 1 - The study context (completed)

  1.1 - The Territorial System (TS)
  1.2 - The Cultural System (CS)
  1.3 - Reconnaissance of the Strategies implemented in the territory
  1.4 - The listening procedure - Territorial laboratories
  1.5 - SWOT
  1.6 - Good Practices

– Phase 2 - Elaboration of the Strategy (subject of the paper)

  2.1 - Strength Idea
  2.2 - Objectives and Actions

    2.2.1 Infrastructures
    2.2.2 Economy
    2.2.3 Tourism

– Phase 3 - Development of Evaluation Tools (in progress)

  3.1 - Construction of action selection criteria
  3.2 - Use of the *SostEc Model* to verify feasibility/sustainability
  3.3 - Identification of tools for impact assessment

– Phase 4 - Application to the case study (subject of the paper, in progress)

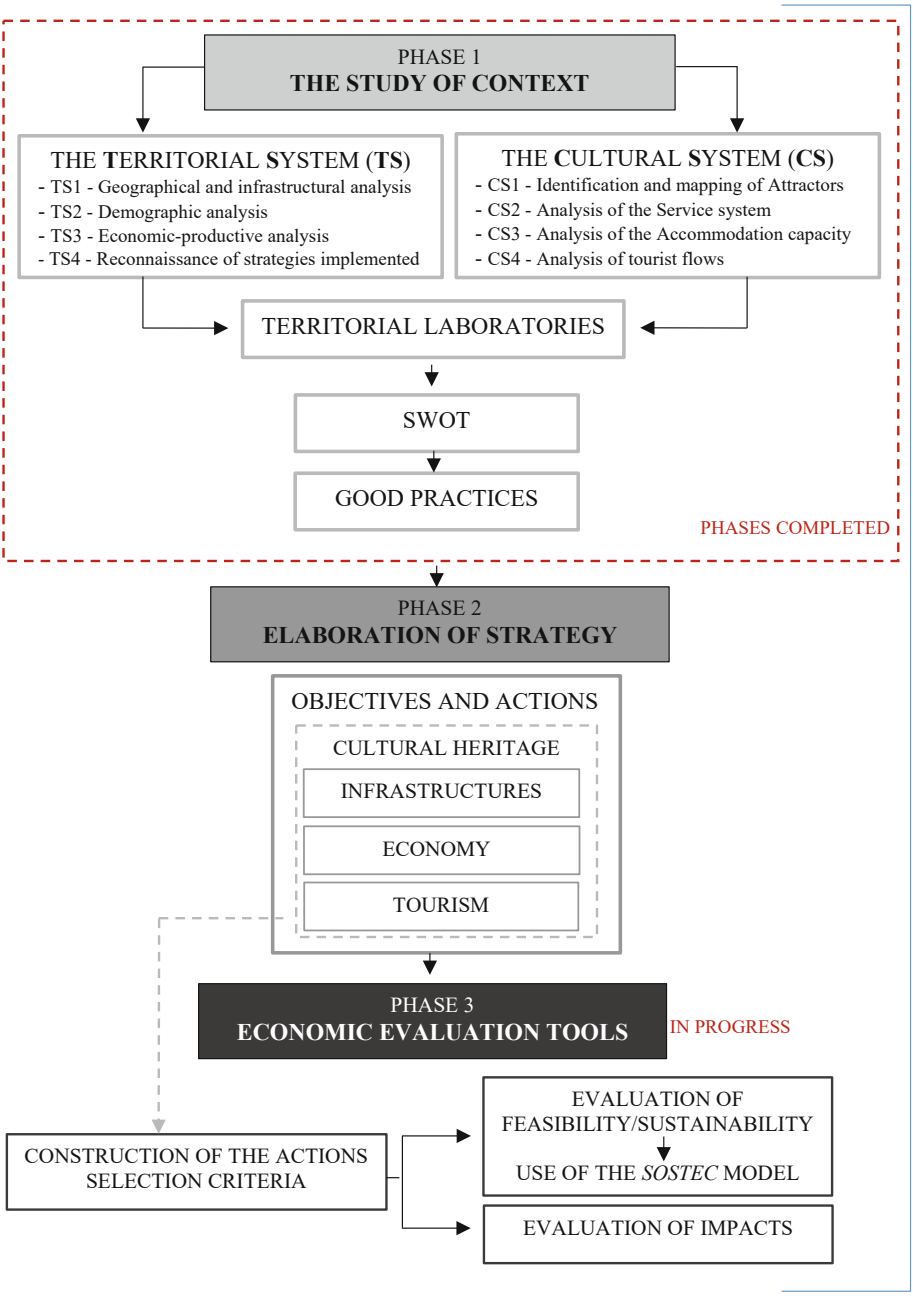

Fig. 1. Methodological approach. Elaboration by the authors, 2023.

With regard to Phase 3, the paper reports the first reasoning on the identification of the most appropriate evaluation techniques for the selection of strategic actions through an integrated approach (use of monetary and non-monetary techniques), deepening in particular the multidimensional evaluation of the effects overall in terms of economic development and revitalization of social and territorial contexts such as inner areas, of changes in social welfare (see point 6).

The paper also reports the initial application results of the proposed methodology (Phase 4) illustrating some experiences already conducted or in progress relating to the strategic actions identified (see point 5.2).

The proposed strategy starts from a resource centered vision, in which local resources are rethought from a vocational perspective, avoiding "patchy" actions. However, this also poses numerous methodological problems, three among all: scale, aggregation, subsidiarity [16].

Therefore, the definition of the area under study was inherent to the scale of the actions that the research intends to undertake. An area of action that was too small would have entailed the risk of an insufficiently incisive impact of the planned strategic actions and attractive capacity. For this reason, reference was made to the wide scale of the Armeni Valley, as representative of an excellent example of a sub-provincial scale with municipalities with very heterogeneous internal characteristics but with some elements in common that could act as a link from an inclusive point of view (see point 4). Within the framework of this complex territorial system, Cultural Heritage is presented as a growing trend and the possibility of outlining development trajectories for marginal destinations, such as inner areas.

The summarized studies are the result of a process that saw the authors as an integral part of a process solicited by the public administrators involved towards the potential of a planning hinged on local resources, then in the complex mediation between different parts and needs.

4 The Study Context

With reference to the case study examined, identified in the so-called "Armeni Valley" of the Metropolitan City of Reggio Calabria (Municipalities: Brancaleone, Bruzzano Zeffirio, Ferruzzano, Staiti), the hypothesis of a new planning strategy is based on the enhancement of the tangible and intangible cultural heritage and on the implementation of related activities (tourist-accommodation and refreshment services; complementary services; sustainable mobility; trade in typical products). A strategy that aims, on the one hand, to activate resources not only related to the tourism-cultural sector, on the other hand to play a significant role in building a network of territorial socio-economic relationships.

To this end, the cognitive analysis of the area in question was preliminarily conducted (Phase 1 - see point 3), already illustrated in more detail in other contexts, which specifically concerned (see point 4.1):

– 1.1 - The analysis of the Territorial System (geographical-infrastructural, demographic and economic-productive analysis)

- 1.2 - The Analysis of the Cultural System (Identification and mapping of material and immaterial Attractors, Analysis of the system of services, accommodation capacity and tourist flows)
- 1.3 - The recognition of the Strategies implemented in the territory
- 1.4 - The listening procedure - Territorial laboratories
- 1.5 - The SWOT analysis
- 1.6 - Good Practices

The Territory - Summary Information. The Armeni Valley (see Fig. 2), is an area not particularly developed from a tourist point of view but characterized by the presence of a valuable material and immaterial cultural heritage and landscape. The analyzes revealed a strong concentration of resources, including the variety of assets of archaeological, architectural (fortification systems and signs of rurality linked to the economies of the hinterland such as the over 160 MiC-Ministero della Cultura registered millstones-*palmenti*) and naturalistic (two municipalities out of four fall within the Aspromonte National Park: Staiti, Bruzzano Zeffirio; two municipalities out of four have a SIC-Sito di Interesse Comunitario: Ferruzzano, Brancaleone; three municipalities out of four fall within the "Costa dei Gelsomini" Regional Marine Park: Ferruzzano, Brancaleone, Bruzzano Zeffirio).

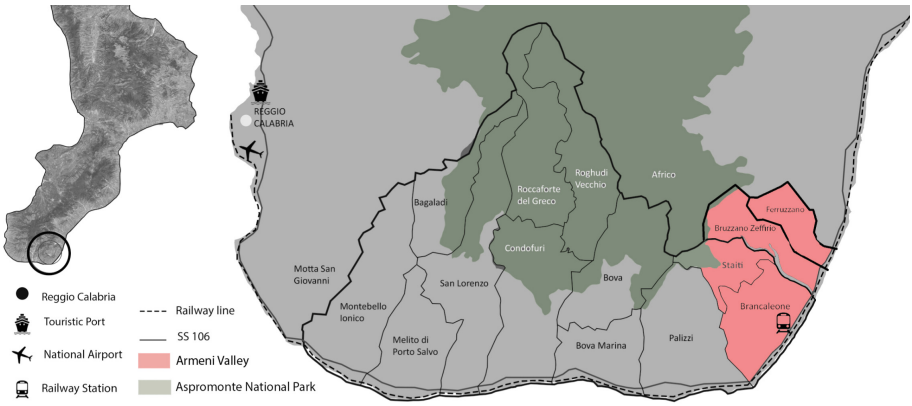

Fig. 2. The context of study - Armeni Valley (RC). Elaboration by the authors, 2023.

The socio-economic situation is mainly characterized by activities related to the tertiary sector and services, and to vocational ones connected to agriculture and the richness of biodiversity of its wine heritage (over one hundred vines with a unique genome currently kept in the Kepòs Conservation Field, Ferruzzano), eleven wineries surveyed by the authors in 2023, with quality productions appreciated on the national and international market connected to the enhancement of local varieties (three certification - D.O.C., I.G.T., D.O.P.).

The flows in the area are mainly connected to summer seaside tourism and return tourism in the June-September period.

The accommodation is characterized by the presence of some structures (hotels, B&Bs) mainly located along the coast, in addition to villages and campsites close to the beaches.

The Listening Procedure. Throughout the process, the participation of stakeholders was taken into account through the organization of local workshops (Phase 2.5), understood as an opportunity to identify the interests of the various actors involved and to enhance their contribution in the co-planning co-construction of the plan.

Territorial listening saw the collection of information from the population, groups, associations and stakeholders through interviews and open dialogues between the parties, which made it possible to understand the different needs, concerns and expectations (see Table 1). This process was essential for defining the strategy (see point 5).

In this scenario, the UNESCO Med Lab and local administrations have used participation as a mechanism to create a critical mass of resources and will to be directed towards a fair, inclusive and sustainable strategic vision.

Table 1. Actors involved in the planning process. Armeni Valley (RC).

Territorial Laboratory	
Coordinator: UNESCO Med Lab	
Municipalities: Brancaleone, Bruzzano Zeffirio, Ferruzzano, Staiti	
Partners: Metropolitan City of Reggio Calabria; MiC - Ministero della Cultura (Soprintendenza Archeologia, Belle Arti e Paesaggio RC-VV); F.L.A.G. dello Stretto	
Artistic-cultural entertainment - Conservatory F. Cilea of Reggio Calabria - Wine Museum of Bianco - House Museum *Zephiros*	*Tourism Sector* - Tour operators - Transport services providers - Touristic Guides - Accomodation providers (n. 8) - Complementary services (n. 2)
Education and research - Mediterranea University of Reggio Calabria - IIS Euclide, Bova Marina - FISAR (Federazione Italiana Sommelier Albergatori e Ristoratori) - *Kepòs* Conservation field	*Associationism* - Rudìna Association - Ferruzzano - Citizen committee *Io ci provo* - Ferruzzano - Pro Loco Bruzzano Zeffirio - AGESCI Gruppo Scout Brancaleone 1
Production sector (food and wine) - Farms (n. 7) - Winery (n. 6) - Food service activities (n. 10)	*Other* - individual personalities who have made their stories and/or skills available (actors, musicians, writers, artists)

SWOT Analysis. The integration of the information gathered from the listening procedure with the surveys conducted by the authors in Phase 2, led to the elaboration of the SWOT analysis (see Table 2) structured on three thematic sectors connected to Cultural

Heritage (Infrastructures, Economy, Tourism). The analysis revealed a great endogenous tourism potential that requires, however, the elaboration of a homogeneous and integrated development project that produces a lasting valorization.

Table 2. SWOT Analysis. Elaboration by the authors.

Strengths	Weaknesses	Opportunities	Threats
Cultural heritage			
Infrastructures			
- Limited distances between centres	- Geographical isolation (Infrastructures and services, public transport) - Decline of rural areas in the absence of support interventions - Progressive abandonment of the centers - youth emigration	- Creation of infrastructures that connect the different nodes	
Economy			
- Quality gastronomic and artisan products	- Low level Standard of services - Seasonality of employment in the cultural sector - Access to resources - Insufficient capacity of entrepreneurship to use the financial resources of public policies - Difficulty of entering national and international commercial circuits - Low level of coordination between actors	- Intersectoral integration of food production and valorization of local artisanal productions - Diversification of the economy - Creation of employment opportunities	- Growth of competition, including traditional wine-growing and agricultural productions of the area - Perception of the local economy as a specialized theme and a sectoral policy - The multiplicity of services as a strength, in the absence of adequate coordination, can produce fragmentation and difficulty in monitoring the evolutionary scenarios of needs

(*continued*)

Table 2. (*continued*)

Strengths	Weaknesses	Opportunities	Threats
Cultural heritage			
Tourism			
- Tangible and intangible heritage of high cultural value - Natural heritage - Vine-growing landscape - Rooted sense of hospitality as a behavioral culture of the communities	- Modest valorization of the territory - Few presence of tour operators - Seasonality of tourist flows - Community maturity (low heritage awareness) - State of conservation of the heritage	- Growing interest in cultural tourism - New trends in the tourism market towards the search for niche products, quality, culture and well-being - Cohesive local area network - Rationalization and renewal of the offer	- Competition and globalization of the tourism market - Prevalence of return and transit tourism and of nearby seaside resorts on the coast - Heritage and environmental emergencies

Good Practices. These considerations include numerous examples of creative planning and possible tools through which to plan on the basis of the enhancement of cultural heritage.

In the national territory (IT), the experiences of the *Sistema Puglia* are particularly interesting. In this case the Wide Area Planning, in line with the provisions of *Documento Strategico Regionale 2007/2013* and of the FESR European Programme, has had a strong development into the *Strategic Plans of Wide Area* (Piani Strategici di Area Vasta) of ten territorial aggregations (Lead institution: Bari, Brindisi, Foggia, Lecce, Taranto, Casarano, Gravina, Barletta, Comunità Montana Monti Dauni Meridionali, Monopoli); these plans outline specific and shared objectives by addressing human and economic resources in the same direction (*Linee Guida per la pianificazione strategica territoriale di Area Vasta - NVVIP Regione Puglia*). These aggregations include the cases of:

– TARANTINA WIDE AREA (twenty-eight municipalities). Strategic objectives of the Plan: construction of a new identity and a unitary image of the territory; promotion of a renewed economic and productive mission; development of an integrated infrastructure system.
– WIDE AREA OF MURGIANA CITY (six municipalities). Strategic objectives of the Plan: to strengthen municipal cooperation; ensure the protection and enhancement of the heritage; open up to the world by improving internal and external accessibility.
– VISION 2020 WIDE AREA (ten non-contiguous municipalities of the new polycentric BAT Province). The vision is based on seven creative cities and visions that represent as many theme-places, proposed as "territorial intuitions", which interpret the themes and opportunities for the development of the territory and its evolution: the City of Rurality; the City of Typical Production; the City of Art; the City of the Sea; the City of Design; the City of Entertainment; the City of Government.

5 Development of the Strategy: The "Armeni Valley" Plan

5.1 Strength Idea

Many inner areas of the South, despite the wealth of natural beauty, history and culture, suffer from economic and development problems due to a lack of strategic planning that takes into account the specificities and potential of the territories, and that is able to attract investments for the incentive of entrepreneurship as a response to the demand for work (contrast to emigration especially among young people). The strategy, therefore, considers the territory in its unexpressed tourist peculiarities as a value, such as traditions, sense of hospitality, events, typicality. Unexpressed peculiarities as, although they are identifying characteristics of the area, they do not represent resources strategically put into the system with a view to enhancing attractiveness.

The "Armeni Valley" Strategic Plan takes the form of a territorial cultural project, based on the so-called "virtuous circle" resource/project/territory [17], which develops a real network of cultural resources and services in the area. This strategy, representative of local interests, is the result of a concerted activity (see Table 1) and of the close connection with the SWOT analysis (see Table 2). For some time now, the administrations involved in the study have launched and fine-tuned a policy of interventions for the recovery and enhancement of excellence, with the aim of starting a significant cultural and economic intervention, on which to base a significant part of the local development policy alternative to those already tested (as of 2021 year before the planning process) (see Table 3). To this end, the four Municipalities entered into a memorandum of understanding in 2022 for technical-scientific support with the UNESCO Med Lab research laboratory active at the PAU Dept. of the Mediterranea University of Reggio Calabria, concerning the strategic planning of the territory connected to the enhancement of the cultural heritage.

Table 3. Implemented Strategies in the cultural sectors (2018–2021). Sources: Open Cohesion, Amministrazione Trasparente of municipalities. Elaboration by the authors, 2023.

Armeny Valley Implemented Strategies - 2018–2021	
Cultural heritage sectors	Expense
Investments on infrastructure	€ 1.754.857,31
Investments on tourism	€ 3.453.395,10
Investments on company incentives	€ 86.981,00
Tot. Investments on cultural sectors	**€ 5.295.233,41**

On the basis of these considerations, the network of the plan was built starting from links in which the role of a center does not depend on its size but on the ability to enter not only economic, but also environmental and cultural exchange circuits (Brancaleone: environmental and economic pole; Ferruzzano: environmental pole; Bruzzano Zeffirio and Staiti: cultural poles), summarizing the complexity of the links present at the local level and their horizontal and vertical dimension.

5.2 Objectives and Actions

The "Armeni Valley" Strategic Plan (see Fig. 3) outlines the Vision of the future of the municipalities involved, through four Strategic Guidelines (SG):

SG1. Community Infrastructures → objectives: to improve the quality of life in inland areas;
SG2. Regeneration of the existing → objectives: reappropriation of spaces and places through alternative uses, creation of identifiable and recognizable polarities;
SG3. Identity Economies → objectives: to create job opportunities to counter youth emigration, discovering, launching and supporting resources and excellence;
SG4. Cultural Tourism → objectives: protection and enhancement of heritage, attraction of investments.

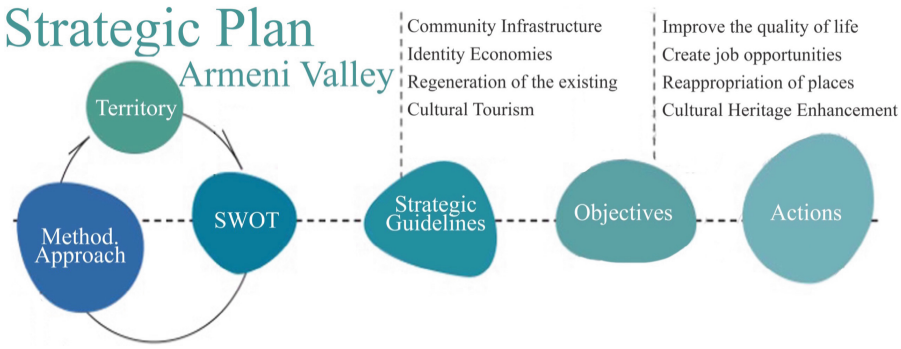

Fig. 3. Armeni Valley Strategic Plan. Elaboration by the authors, 2023.

On the basis of the characteristics of a strategic plan compared to other territorial and urban planning instruments, and with reference to the SWOT analysis, the possible strategies and the desirable actions and open options have been defined, rather than setting certain objectives and outlining a pre-established future; therefore, a unitary body of concepts and procedures was not defined, but rather a field of experiments and experimentation. For the realization of the future scenario, the Strategies listed below have been outlined with the related Actions (see Table 4), adapted, during construction, to the indications of local, national and European policies in order to make the Strategic Plan instrument of service to be able to identify the right opportunities given e.g. from the National Recovery and Resilience Plan.

The envisaged actions include some activities consolidated in recent years and others in progress or in the planning and experimentation phase, each pertaining to one or more project partners, coordinated by the UNESCO Med Lab and assisted by the administrations (see Table 5).

Table 4. Strategies and Actions. Elaboration by the authors, 2023.

Sectors		Weakness (W)	Strategic Guidelines (SG)	Objectives (O)	Actions (A)
Cultural Heritage	Infrrastuctures	W1. Geographical isolation (Infrastructures, services, public transport) W2. Progressive abandonment of inner centers	SG1. Community Infrastructures SG2. Regeneration of the existing	O1. Improving the quality of life O2. Reappropriation of spaces and places O3. Creation of identifiable and recognizable polarities	A1. Recovery and maintenance of public spaces and buildings with historical-cultural value for localization of local productive activities or community services A2. Improvement of public/private transport
	Economy	W3. Low level of standard services W4. Seasonality of employment in the cultural sector W5. Insufficient ability of business to access resources W6. Difficulty of entering commercial circuits W7. Low level of actors' coordination	SG3. Identity Economies	O4. Generate investment and job opportunities O5. Countering youth emigration O6. Relaunch and support resources and excellence O7. Encourage forms of collaboration (public-private)	A3. Implementation of partnership forms A4. Building a territorial e-commerce platform A5. Design of composite packages of services
	Tourism	W8. Modest enhancement of the heritage and resources W9. Seasonality of flows W10. State of conservation of heritage	SG4. Cultural Tourism	O8. Protect and enhance the Heritage O9. Attract investment O10. Seasonal adjustment of flows	A6. Design and implementation of knowledge tools A7. Territorial marketing, development of a communication plan A8. Enrollment to national and international circuits

Table 5. Plan Actions to march 2023. Elaboration by the authors, 2023.

Actions (a)	Projects (p)	Fund	Timing	Expense
Cultural heritage sectors				
Infrastructures				
A1. Recovery and maintenance of public spaces and buildings with historical-cultural value for localization of local productive activities or community services	P1. Multifunctional Urban Park "Nature&Health"	PNRR, Mission 5, Component 2, Investment 2, Intervention line 2.2	2022	€ 1.500.000,00
	P2. Parco Inclusivo "Play for All"	PNRR, Mission 5, Component 2, Investment 2, Intervention line 2.1	2022	€ 650.000,00
	P3. Widespread hotel, Brancaleone	to locate	2022	€ 1.140.000,00
	P4. Accommodation and spa project "Il Palazzo delle Essenze", Cundari Palace, Brancaleone	to locate	2022	€ 1.340.000,00
	P5. Accommodation project "Stay It!", Musitano Palace, Staiti	to locate	2022	€ 3.130.000,00
	P6. Community social infrastructure "Fare Spazio all'Accoglienza"	PNRR, Mission 5, Component 3, Investment 1, Intervention line 1.1	2023	€ 550.000,00
	P7. Community social services "Fare Spazio all'Accoglienza"	PNRR, Mission 5, Component 3, Investment 1, Intervention line 1.1	2023	€ 450.000,00
A2. Improvement of public/private transport	P8. Car Sharing Armeni Valley	to locate	ongoing	€ 268.000,00
Economy and Services				
A3. Implementation of partnership forms	P9. Armeni Valley Network	Self-financing of partners	ongoing	€ 15.000,00
A4. Building a territorial e-commerce platform	P10. Armeni Valley web-site	Public subjects involved and commercial operators	ongoing	€ 100.000,00

(*continued*)

Table 5. (*continued*)

Actions (a)	Projects (p)	Fund	Timing	Expense
Cultural heritage sectors				
A5. Design of composite packages of services	P11. Construction of cultural routes integrated with territorial services	Public funds of involved municipalities - (Agreemen with UNESCO Med Lab)	2022	€ 30.000,00
Tourism				
A6. Design and implementation of knowledge tools	P12. Information and dissemination "The Armeni Valley storytelling"	Public funds of involved municipalities - (Agreemen with UNESCO Med Lab)	ongoing	€ 20.000,00
	P13. "Seguici! A passo lento" Support measures for Libraries and Public Historical Archives	POR CALABRIA FESR-FSE 2014–2020, Action 6.8.3	ongoing	€ 60.000,00
A7. Territorial marketing, development of a communication plan	P14. Sea Museum "MUSAMA" Communication Plan, Brancaleone	to locate	ongoing	€ 80.000,00
	P15. Museum of Italian-Greek Saints Communication Plan, Staiti	to locate	ongoing	€ 40.000,00
	P16. Kepòs conservation field, Ferruzzano	to locate	ongoing	€ 200.000,00
A8. Enrollment to national and international circuits	P17. Candidature to CoE Cultural Route "Iter Vitis"	Public funds of involved municipalities	2022	€ 15.000,00
TOT. INVESTMENTS STRATEGIC PLAN				€ 9.588.000,00

Below are the specifications of the most advanced Actions (see Table 5).

Actions A.1–A.8. Actions A.1 and A.8 were matched by a series of interventions, for a total amount of €8,760,000.00, aimed at:

– recovery of public spaces (P.1–2) for the construction of infrastructures to support the quality of life and well-being (in connection with the Aspromonte National Park) of citizens and tourists;

– recovery of public buildings or buildings of public value of particular historical-architectural value for the location of tourist services (P3–5: accommodation businesses, educational laboratories, wellness and spa) and for the community (P6).

Action A2. The theme of accessibility and mobility is one of the transversal critical elements to development (see Table 2) and represents one of the major problems for the permanence of the populations, above all for the communities residing in the more inland areas. Action A.2 includes a feasibility study on the "Armeni Valley Car Sharing" project which envisages, in support of the local infrastructure serving citizens and tourists, the purchase of seven electric cars and the installation of five electric columns and relative stalls in correspondence with the main cultural attractions and infrastructural nodes (Railway Stations) for a total amount of € 268,000.00 (see Fig. 4).

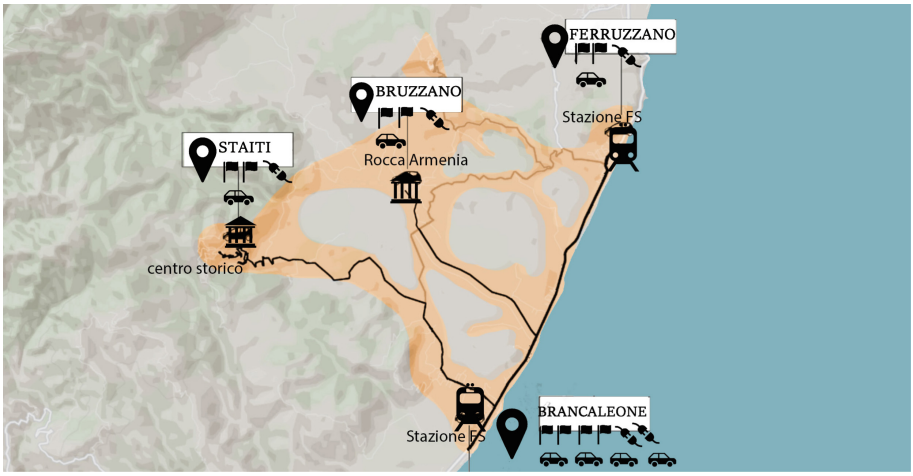

Fig. 4. Car Sharing project. Elaboration by the authors, 2023.

Actions A.5–A.7. The planned actions concern the specific potential of the territory and are aimed at developing innovative ways of interpreting and re-proposing them, through effective communication and the provision of a Territorial Marketing Plan and individual resources (P14–15–16). These actions are expressed in a new tourist strategy of integrated and seasonally adjusted services, expressed in thematic itineraries built by the UNESCO Med Lab, based on the quality of the offer and oriented towards a new way of experiencing tourism, cultural tourism.

Action A.8. Specifically for action A.8, we report the process conducted by UNESCO Med Lab, within the framework of the Institutional Agreement, which led to the candidacy and inclusion of the Armeni Valley in the Cultural Route of the Council of Europe Iter Vitis "Les Chemins de la Vigne" [18], inserting its heritage, not only wine, in an international circuit.

The objective of the itinerary is to safeguard wine biodiversity, promoting its uniqueness as an important part of the European and Mediterranean economy.

The main evaluation criterion for joining is demonstrating the presence of a wine-growing production tradition, ancient native vines and an art/archaeological heritage linked to viticulture [19].

In the candidacy project, the first choice to be made was the area of intervention, from single places part of the route (e.g. Santa Maria De' Tridetti, Staiti) to larger portions of the territory (e.g. Aspromonte National Park, Regional Marine Park "Costa dei Gelsomini", Bosco di Rudìna, millstones/palmenti of Ferruzzano) to the common connecting elements (the wine landscape); hence the use of an approach that did not envisage buffering with the creation of a territorial corridor in conflict with the assimilation of the itinerary to territorial networks [20].

The "Iter Vitis" brand has proved to be a powerful catalyst; while not wanting to diminish the value of the founding phases, the territorialization of the brand was the moment that decreed a concrete implementation of the itinerary instead of its being reduced to a brand with no repercussions on the territory, to a logo to be associated.

6 First Conclusions and Research Perspectives in the Field of Economic Evaluation

Given the many expectations placed on development opportunities connected with the enhancement of cultural heritage in the framework of strategic planning, and considering that the promotion of places necessarily passes through the activation of public investments, it is important to evaluate the expected impact of these operations (see Table 4) and the measurement of the increase in competitiveness and attractiveness of a territory through the identification of specific synthetic indicators [21, 22].

On this theme, the study includes some reasoning in progress which make the different theoretical perspectives operational, which will be the subject of subsequent insights (see Fig. 5).

The selection criteria of Actions will be identified on the basis of:

- feasibility/sustainability evaluation;
- evaluation of effectiveness.

Specifically, to verify the economic-financial feasibility/sustainability of the projects relating to the actions (see Table 5), the SostEc Model was used, conceived and tested by the authors in other contexts [23, 24]. The model includes the verification of the organizational-management models assumed through the construction of the Economic and Financial Plan (E.F.P) and the Discounted Cash Flow Analysis (D.C.F.).

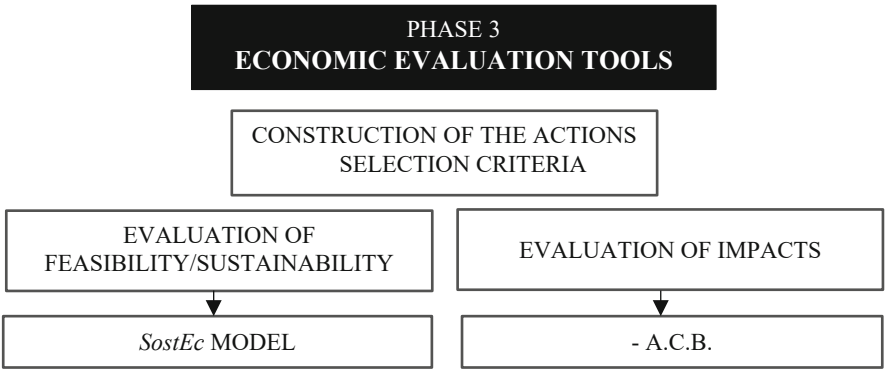

Fig. 5. Phase 3. Elaboration by the authors, 2023.

With regard to the evaluation of effectiveness, on the other hand, the first reasoning connected to the estimation of impacts through an integrated approach (use of monetary and non-monetary techniques) is underway, investigating in particular [25–27]:

– the multidimensional evaluation of the overall effects generated, in terms of economic development and revitalization of social and territorial contexts such as Internal Areas, of changes in social well-being [28, 29];
– the identification of the system of public and private conveniences and of the economic mechanisms for balancing them for the purposes of feasibility and sustainability, in a long-term time horizon [30].

The research carried out has allowed, on the one hand, to recognize the necessary value of communities in development, offering possible guidelines and a framework of strategic choices that outline various opportunities for the territories concerned [31].

A process on a wide area scale which is characterized by an economic, social and territorial interdependence of the municipalities which does not necessarily coincide with an administrative border, in which each center assumes a specific role according to the relationship it develops with the strategies identified and the role of signifier that it assumes in the local context, reading the different levels of the existing relationships with the territory on a thematic basis (infrastructural, cultural, economic). Innovation consists in starting the choices concerning the development of the territory from the enhancement of the Cultural System through a vision of the system. The peculiarity of the approach used is that of considering the active role of local subjects, who are called to play a leading role in planning and in a radically innovative governance practice for the context.

At first glance, however, the process of co-construction of the plan is still incomplete. In fact, another line of research was launched in parallel, which concerns the strengthening of the attractiveness of the territory through the construction of a network with other areas of the province; hence the current integration strategy of the municipalities of Bivongi, Bova and Camini.

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Assessment of Public Health Performance in Relation to Hospital Energy Demand, Socio-Economic Efficiency and Quality of Services: An Italian Case Study

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Abstract. This study investigates the relationship between energy management and hospital performance in the Italian public healthcare network. Using data on energy consumption and hospital activity from 28 public Italian hospitals, we conducted a regression analysis to assess the impact of organizational efficiency and patient hospitalization propensity on energy costs. Our results show that an increase in organizational efficiency is associated with an increase in energy costs, while an increase in patient hospitalization propensity is also associated with an increase in energy costs. However, some hospitals showed a higher energy cost per capita than the average, indicating the need for better energy management practices. We suggest that better management of human resources could be more effective in reducing energy costs than purchasing new equipment and expanding structures. Additionally, we highlight the importance of developing guidelines for energy consumption management, prioritizing the acquisition of alternative or renewable energy, and designing, constructing, and managing hospital buildings with a focus on energy efficiency. These findings have important implications for policymakers and hospital administrators as they work to balance quality of care with economic efficiency.

Keywords: Public healthcare performance · Socio-economic efficiency · Territorial healthcare system planning

1 Introduction

Good health is essential to sustainable development, as established by the 2030 Agenda. Indeed, health has a central position in Sustainable Development Goal 3, which concerns "Good Health and Well-being." The goal also aims to achieve universal health coverage

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and provide access to safe and effective medicines and vaccines for all. It is closely linked to over a dozen targets in other goals related to urban health, equal access to treatments, and non-communicable diseases, among others. In fact, it represents a unique opportunity to promote public health through an integrated approach to public policies across different sectors. Specifically, Target 3.8 "Achieve Universal Health Coverage" aims to provide universal health coverage, including financial risk protection, access to quality essential health care services, and access to safe, effective, quality, and affordable essential medicines and vaccines for all.

Subsequent paragraphs, however, are indented. Despite this awareness underpinned by ambitious goals in recent decades, there has been a steady increase in the number of disasters, including pandemics, which have had significant impacts on societies and economies. The COVID-19 pandemic has shown that many countries around the world have been caught unprepared to deal with such a threat, and the safety net provided by the health infrastructure has failed even in the most developed countries, with considerable fallout and repercussions on the health sector in general. This has led to an increase in healthcare costs, with forecasts of a further upward trend, without an integrated system for monitoring the efficiency of the healthcare system in general and the quality of services in particular.

Therefore, the interest of academics, healthcare managers, and policymakers has increased in identifying measures to contain healthcare spending while ensuring service quality. In this context, various attempts have been made to improve provider efficiency, including activating competition between hospitals and the implementation of incentive-based payment systems. Proposed models aimed at maximizing public administration and social housing have demonstrated effectiveness in meeting public needs while ensuring fair compensation for private entities (Morano et al., 2021). Numerous studies have been conducted to assess hospital efficiency and its variation over time, in order to provide an accurate estimate of hospital productivity and costs, which can be used as a criterion for payment for hospital services and to improve national health provision. As a matter of fact in many countries, public policies concerning the reduction of beds and medical and nursing staff, hospital mergers and acquisitions, and lower investments in health infrastructure are now being reassessed. In addition, the decentralised organisation of the healthcare system is also being questioned, and in many cases, the re-centralisation of the system is being considered. Italy is one of the Western countries that has significantly reduced healthcare spending and decentralised management to the regional level. However, the effects of these policies are still being debated. Moreover, despite the changes in healthcare organisation, inequalities between regional systems have not decreased over the last 20 years. In the literature, there is still a broad consensus that these decentralisation plans, and the decentralisation process in general, have had an impact on increasing health inequalities not only between but also within regions.

Moreover nowadays, healthcare managers must consider the impact of exogenous economic factors, such as the progressive increase in the cost of energy resources throughout Europe, an increase that is even more relevant following the outbreak of the conflict in Ukraine and the inflationary spiral that is still in progress. According to the National Agency for Regional Health Services (AGENAS), funding of EUR 1.6

billion has been provided for the National Health Service entities for the year 2022 to counter the effects of the increase in the prices of energy sources.

Given this evidence, the assessment of the territorial health services usually crosses several dimensions to obtain a comprehensive composite indicator useful for classification and comparisons. Therefore the first contribution of the present work is to identify and measure the main latent variables that summarize the organizational components of public nosocomial facilities, as well as variables that can express patients' preferences for hospital choice based on best activity or outcome criteria. The second contribution of this paper presents a machine learning methodology using machine learning algorithms that can assist decision-makers in their choices. The third contribution explains the interaction between identified hospital components and per capita health expenditure on electricity through a linear regression model.

The paper is organized as follows: after introducing the problem and aims of the work, the next paragraph presents the methodological background and the case study to which it was applied. This is followed by a chapter with details of the study conducted, where most interesting results are presented and are then critically discussed in the following chapter along with an assessment of the proposed approach's innovativeness, potential, and limitations. The conclusions offer considerations of the methodology's implications for decision support at different scales and outlines possible follow-ups.

2 Background

In the literature, it has been observed that various demographic and economic factors play a role in the choice of healthcare facilities, such as income, propensity to travel, level of education, age, type of illness, need for frequent treatment, and trust and reputation of the facility and its operators.

The patient's decision-making process when considering the quality of services (real or perceived) can be divided into several stages, including information gathering, risk/benefit assessment, consultation with the physician, and choice of treatment. The patient experience is complex and depends on several factors, including satisfaction, quality of care, and effectiveness of the healthcare system (Wolf et al., 2021). The perceived quality of healthcare is related to the actual quality of care provided (Doyle et al., 2013). Patients' satisfaction with the healthcare system is influenced by their experience of care and their perception of adequate attention to their care needs (Bleich et al., 2009). Active patient involvement in treatment choice improves patient satisfaction (Shay & Lafata, 2015). From the perspective of hospital facilities, a significant factor for perceived quality is the facility's ability to effectively treat complex and specialized illnesses, i.e., the facility's specialization and the complexity of the clinical cases treated. Another essential aspect is the reputation of the doctors working there. These factors can be emphasized by marketing policies pursued (Falavigna & Ippoliti, 2013).

According to the literature, two main points of view need consideration when evaluating possible measures: social welfare and stakeholder theory. Hospitals should not only ensure high-quality medical services at reasonable costs to improve health in society, but also be concerned about the well-being of their customers and all other stakeholders involved in the process (Hajiagha et al., 2023).

Based on these assumptions, hospital management should be aware of all the variables that express the structure's human, financial, and technological resources, as well as the outcomes produced and the quality of life of patients. To obtain timely decisions by healthcare management with the aid of streamlined procedures and tools, methodologies based on Multi-Agent Simulation to support Decision-Making in healthcare infrastructures for the organizational management and actionable choices in health risk (Esposito et al., 2020), as well as methods based on Dynamic Network Visualization of space use to support spatial redesign related decisions to improve workflow effectiveness and patient well-being (Esposito & Abbattista, 2020), have been proposed.

Artificial intelligence-based approaches composed of optimization and machine learning (Mirmozaffari et al., 2022) have been conducted and applied in different fields and organizations to calculate, for example, public hospital efficiency (Hajiagha et al., 2023), rather than in the industrial and service sectors (Guede-Cid et al., 2021).

As such methodologies involve large volumes of data, they require data mining techniques such as feature extraction, selection, and classification to derive meaningful information from the data. Feature selection is a technique used to reduce dimensionality to prune the feature space and, consequently, reduce computational cost and improve classification accuracy by means of Principal Component Analysis (Alomari et al., 2022).

To overcome the limitation of the dimensionality of the available data, this study proposes, by means of Principal Component Analysis (PCA), a reduction in the number of variables available in national databases and frequently used in the literature for measuring hospital efficiency. The PCA will identify two distinct principal components, expressing respectively a summary of the hospital organization and an outcome of the propensity to hospitalize patients based on perceived quality. Furthermore, the relationship between hospital energy cost and the two identified components will be studied by applying a linear regression. The predictive values obtained for the 28 public hospitals will be discussed by applying an ANOVA analysis. The analyses performed in this study will be conducted in a machine learning environment.

This paper presents a case study of the Apulia region (Italy). The regional health system encompasses both public and private accredited facilities within a given region, forming an organized complex known as the regional health industry (Falavigna & Ippoliti, 2013). The Regional Health Service in Apulia is represented by six Aziende Sanitarie Locali (ASLs), as shown in Table 1. ASLs are public legal entities with autonomy in organizational, managerial, technical, administrative, patrimonial, and accounting matters, as well as entrepreneurial autonomy (in accordance with Article 3 of Legislative Decree No. 502 of 30 December 1992). ASLs are part of the National Health Service.

This study focuses on the regional public hospital network in Apulia, specifically analyzing 28 facilities as indicated in the National Health Service Data Bank of the Ministry of Health. The public network consists of 24 ASL Direct Hospitals, one Hospital Authority integrated with the National Health System (NHS), one Hospital Authority integrated with the University, and one Public Institute for Hospitalization and Scientific Care. Some facilities, as specified in the single hospital reorganization document approved by the Apulian Regional Council on 03/07/2019, have connected plexuses and/or hospitals located in different places from the main structure. Thus, for greater

accuracy in measuring the distance traveled by patients, all the physical plexuses indicated in the National Outcomes Plan have been considered. The total number of facilities considered for measuring the active mobility of Apulian patients is 37 (see Fig. 1), including admissions made by ASL and by territorial ambit, as indicated in the National Outcomes Plan.



Fig. 1. Division of regional territory into provinces and public hospitals in Apulia.

In terms of hospital classification in Apulia, there are 5 s-level hospitals, 12 first-level hospitals, 2 Scientific Hospitalization and Care Institutes (IRCCS), and 9 basic hospitals. The differences between these types of hospitals are described in the Ministry of Health's regulations on the definition of qualitative, structural, technological, and quantitative standards for hospital care, which are implemented under Article 1, paragraph 169, of Law no. 311 of 30 December 2004 and Article 15, paragraph 13, letter c) of Decree-Law no. 95 of 6 July 2012, converted with amendments by Law no. 135 of 7 August 2012. The hospital levels differ primarily based on catchment area, number of wards, and complexity.

3 Methodology

A literature review was conducted to identify variables commonly used in studies on hospital efficiency. The dataset used in this study was obtained from the National Health Service of the Ministry of Health and the National Outcomes Plan of the National Agency for Regional Health Services.

The variables considered for calculating hospital efficiency were: Human resources: Variables related to the number of doctors, nurses, and general hospital staff employed in the hospital; Capacity: Variables related to the hospital's capacity to receive and treat patients, including the number of beds and wards; Productivity: This variable refers to the number of patients treated and admitted to the hospital; Quality of care: This variable assesses the quality of care provided to patients through quality indicators, such as mortality, hospital readmissions, and surgical discharges; Patient length of stay: This variable refers to the length of time a patient stays in the hospital; Patient satisfaction: This variable assesses patients' satisfaction with the care they received in the hospital.

The 16 variables considered for the 28 public facilities in the Apulia Region were divided into two groups. The first group included variables related to the hospital's workforce and facility capacity, while the second group included the other variables. Table 1 presents the variables in each group. Note that variable Var_10 is a derived multiplicative indicator that measures intraregional active mobility and will be explained separately in Sect. 3.1.

Table 1. Organization variables of Apulia Public Hospital.

Organization variables	Definition	Reference No	Data sources
Var_1	No. of day hospital beds	Fang and Lahdelma (2016)	NHS Database
Var_2	No. of day surgery beds	Fang and Lahdelma (2016)	NHS Database
Var_3	No. of beds in ordinary hospitalization	Fang and Lahdelma (2016)	NHS Database
Var_4	No. of beds used	Fang and Lahdelma (2016)	NHS Database
Var_5	No. of departments used	Briestensky and Kljucnikov (2021)	NHS Database
Var_6	Total no. of physicians	Fang and Lahdelma (2016)	NHS Database
Var_7	Total no. of nurses	Fang and Lahdelma (2016)	NHS Database
Var_8	Total no. of hospital staff	Fang and Lahdelma (2016)	NHS Database

In the second group, we have included outcome variables that express the hospital's performance in terms of services provided and outcomes produced, rather than active mobility and thus the attractiveness of the facility (Table 2). The combination of these factors will contribute to the overall perceived quality of care by patients.

The methodology proposed in this paper involves a first phase of applying Principal Component Analysis (PCA) to the initial dataset. The dataset will be reduced in size by applying two distinct PCAs to the two groups of variables identified. The Principal Component for the first group will express Hospital Organisation, while the Principal Component for the second group will express Patient Admission Propensity.

The effects of climate change, along with the recent energy crisis, have brought energy efficiency issues in hospitals and the increased demand for more research on energy efficiency in buildings into the spotlight (Psillaki et al., 2023). Therefore, we included an additional study variable: the per capita cost of medical electricity per Apulian resident in relation to the number of physicians in the year 2020. This variable was calculated as the ratio of the resident population of the Apulia Region in the year 2020 divided by the number of physicians in each hospital (Gutierrez-Romero et al.,

Table 2. Outcome variables of Apulia Public Hospital.

Outcome variables	Definition	Reference No	Data sources
Var_9	No. of hospitalizations	Fang and Lahdelma (2016)	NHS Database
Var_10	Intra-regional mobility active by territorial scope	Colombi et al. (2017)	National Outcomes Plan
Var_11	No. of deaths at 30 days after hospitalization	Bleich et al. (2009)	National Outcomes Plan
Var_12	No. of interventions according	Fang and Lahdelma (2016)	National Outcomes Plan
Var_13	No. of hospital readmissions at 30 days after hospital discharge	Personal communication	National Outcomes Plan
Var_14	No. of inpatient days	Fang and Lahdelma (2016)	NHS Database
Var_15	No. of available days indicated	Fang and Lahdelma (2016)	NHS Database
Var_16	No. of surgical discharges	Personal communication	NHS Database

2021), multiplied by the value of the per capita health expenditure related to the energy costs of Apulia in the same year (AGENAS).

The methodological workflow, shown in Fig. 2, is a graphical representation of the complex analyses applied in this study using data analysis and machine learning tools, via the widgets available in the Orange software.

We chose to use the Orange software for our analyses because it represents a robust data mining tool (Mirmozaffari et al., 2022).

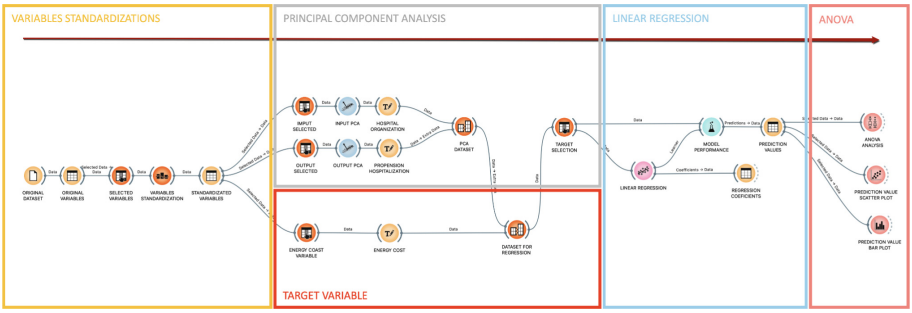

Fig. 2. Methodological workflow implemented in Orange. (Color figure online)

The new dataset, which includes the two identified principal components and the value of energy expenditure per capita of the population distributed by doctor, will be

subjected to training and testing by means of 10-fold cross validation. Linear regression will be used for this process. The learning algorithm (regressor) will process the input dataset and produce as output a prediction model capable of identifying the value of healthcare energy expenditure for given values of hospital organization and propensity to hospitalization of patients.

3.1 Intra-regional Mobility Active by Territorial Scope

In Italy, the Italian National Health Service has delegated management, economic, financial, administrative, organizational, managerial, etc. independence to the regions, while citizens are free to choose where to seek treatment throughout the country. While freedom of choice in seeking treatment can be considered an opportunity as well as a citizen's right, which must be protected (Nante et al., 2021), it is evident that the right to access and enjoy proximity to quality and affordable levels of care is equally important. In fact, mobility is not only due to preferences for specialized care but is often forced by gaps in local supply, such as a lack of beds or waiting time. Hence, strong territorial disparities in the supply of healthcare services can cause social injustices that must be equalized, hopefully upwards. In this sense, mobility for care is a crucial proxy index for measuring the state of the national public health service supply and for supporting healthcare policy design and hospital management.

The phenomenon of interregional migration flows of patients for care has been widely documented in the literature (Balia et al., 2018). Obvious discrepancies between the north and south of the country have been noted, and the consequences of the pattern of reimbursement for extra-regional care generate a financial flow in favor of wealthier regions, exacerbating the North-South divide in the National Health Service (Berta et al., 2021). A finer analysis of patients' travel patterns on a regional scale is necessary to identify the determinants of travel and to assess hospital attraction areas (i.e. catchment areas) that are linked to the services offered by individual hospitals that are part of each regional care network.

This is crucial to offer regional decision-makers and individual hospital managers benchmarks for evaluating the efficiency of the internal system and of each facility that is part of it. This allows for the more immediate identification of the causes of weakness in the system, such as poor quality supply or quantitatively insufficient availability compared to demand, on which to intervene with decisions at various scales. Similarly, it is useful for the recognition of hidden excellence to support decisions aimed at reproducing and disseminating the best practices already available in the regional health system and often unknown and undervalued.

In the present study, a patient's decision to seek treatment where they perceive better quality, subject to their economic availability and the medical offer proposed, is considered. 'Positive mobility' is defined as the flow of 'immigrants,' residents in the Apulia Region in 2020, who reach a hospital located in a different ASL from the one where the patient is a resident. Only intra-regional movements, i.e., within the region, made by patients resident in the region, have been evaluated. Therefore, admissions of non-resident patients are not considered. Since it is an evaluation of a closed system, only active mobility was taken into account since the difference with passive mobility would have produced no difference.

To calculate intra-regional active mobility in kilometers, we first calculated the interpolated distance between the capital city of the ASL where the patient resides and the city where the hospital providing the service is located (Dist kmHospi) (Falavigna & Ippoliti, 2013). Subsequently, we added the total active hospitalizations by ASL (HospiASL) and by territorial area (HospiArea), respectively, for each hospital. Finally, we calculated the intra-regional active mobility in kilometers by applying the following formula:

$$\text{Var_10} = \textit{Active mobility}_{\textit{infra regional}} = (\textit{Hospi}_{ASL} + \textit{Hospi}_{Area}) * \textit{Dist km}_{Hospi}$$

The movement made by the patient to a different territory from that of residence is considered to be due to a better perception of the quality of the service received. Although the displacement has been calculated by convention, along a hypothetical straight line, it would be interesting to measure the actual route that the "health client" would have to face to reach the hospital providing better "quality", while also analyzing other socio-economic factors that contribute to this choice.

3.2 Principal Component Analysis

Principal Component Analysis (PCA) is a machine learning technique that reduces the complexity of a dataset by transforming a set of original variables into a new set of linearly independent variables, called principal components. This method simplifies the representation of the data while retaining the most important information.

By reducing the size of the original variables, it is optimized while preserving as much information as possible. The transformation of the data takes place in a new coordinate system, where the new variables are orthogonal and arranged in order of importance (Hastie et al., 2009). PCA was used as a pre-processing phase of the data in a machine learning environment. We used Orange's select column widgets to split the initial dataset into the two groups of Input Variables (Table 1) and Output Variables (Table 2). We then linked the two groups to the PCA widgets, as illustrated in Fig. 3.

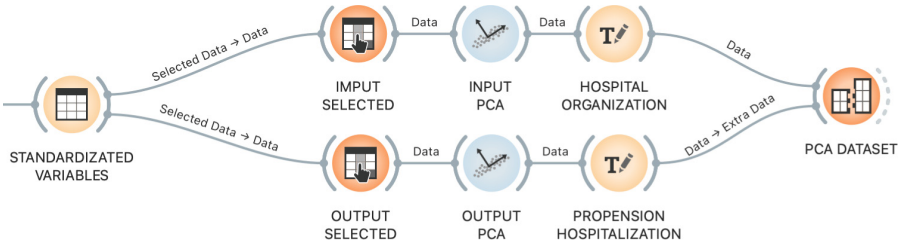

Fig. 3. PCA workflow.

Applying PCA to the first group of identified variables (Table 1), we obtained a principal component (Input_PC1) preserving almost 90% of the total variance with minimal loss of information. The graphical representation is shown in Fig. 4.

Applying PCA to the second group of identified variables (Table 2), one main components (Output_PC1) was identified, preserving almost 93% of the total variance. The graphical representation is illustrated in Fig. 4.

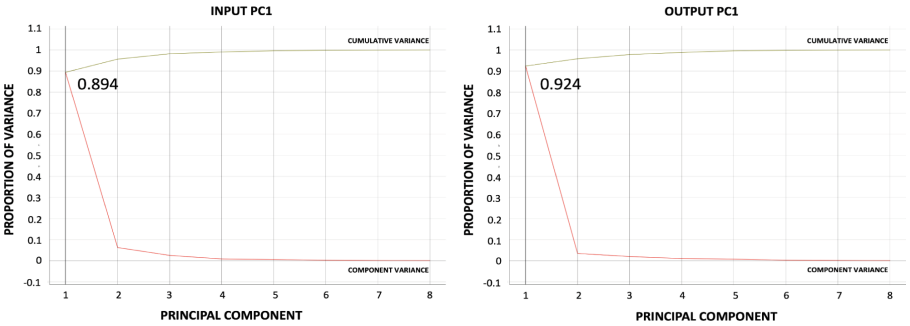

Fig. 4. Input PC1 and Output PC1 variance representation.

The incidence of the individual original variables on the main components can be visualised by means of the data table widget. The results produced and represented in Fig. 5 for the first principal component show a distribution in terms of incidence, which is fairly homogeneous across all variables and therefore PC_1 was renamed Hospital Organisation.

Data instances: 1
Features: 8
Meta attributes: 2

	components	variance	VAR_1	VAR_2	VAR_3	VAR_4	VAR_5	VAR_6	VAR_7	VAR_8
1	PC1	0.894017	0.331244	0.290424	0.368028	0.361608	0.367425	0.369782	0.369161	0.362916

Fig. 5. Incidence of Input variables on Input PC1.

The main output component was renamed Hospitalisation Propensity. The results are illustrated in Fig. 6.

Data instances: 1
Features: 8
Meta attributes: 2

	components	variance	VAR_9	VAR_10	VAR_11	VAR_12	VAR_13	VAR_14	VAR_15	VAR_16
1	PC1	0.923857	0.365744	0.338618	0.33546	0.3532	0.349674	0.364054	0.359203	0.36118

Fig. 6. Incidence of Output variables on Output PC1.

3.3 Machine Learning Algorithm

Linear regression is a statistical model that attempts to establish a linear relationship between a dependent variable (target) and one or more independent variables (features) (Fang & Lahdelma, 2016).

The linear regression model produces a linear function that attempts to predict the value of the dependent variable based on the values of the independent variables.

The model in multiple linear regression consists of more than one predictor variable:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_P X_P + \varepsilon$$

where Y is the response variable, $X_1; X_2; \ldots X_P$ is the predictor variables with p as the number of variables, $\beta_0; \beta_1; \beta_2 \cdots \beta_P$ are the regression coefficients, and ε is an error to account for the discrepancy between predicted data and the observed data (Fumo & Rafe Biswas, 2015).

3.4 Target Variable

Sustainability issues have become fundamental in all their various environmental, social and economic facets. One of the main challenges to be overcome by hospitals in this regard is energy management, based on environmental sustainability, which is used as a strategic means to achieve competitiveness and focuses on energy efficiency that includes policies, strategies and technologies designed to reduce energy consumption, pollutant gas emissions and costs (Borges de Oliveira et al., 2021).

Therefore, efficient energy management in hospitals has the potential to improve energy efficiency on the one hand and better management of public expenditure on health energy on the other.

Based on this assumption, in this study the per capita expenditure of the Apulian population in the calendar year 2020, distributed by hospital doctors, was identified as the target variable.

To calculate the cost of energy, we first calculated the ratio between the resident population in Apulia in 2020 ($Tot_{Res_{ASL}}$) and the total number of doctors in both public and private accredited hospitals, for each ASL ($Tot_{Doctors_{ASL}}$).

We then multiplied this ratio by the number of doctors in each public hospital, weighted by ASL ($Doctors_{Hospi}$) The resulting value for each facility, which is an expression of the population catchment area, was then multiplied by the per capita health energy cost of € 21.45 for the Apulian population in the year 2020, as indicated by the National Agency for Regional Health Services (AGENAS).

$$Energy\ cost = \left(\frac{Tot_{Res_{ASL}}}{Tot_{Doctors_{ASL}}} \right) * Doctors_{Hospi} * 21.45$$

4 Results and Discussion

It describes the second phase of the study, in which the target variable is "Per-capita energy cost" and the features are "Hospital Organisation" and "Hospital Propensity".

The Linear regression widget is used to provide the prediction algorithm with the dataset containing the variables to be analysed, and the performance of the model is evaluated using the Test and scores widget with a cross-validation of 10 folds. The results of the evaluation are described in Fig. 7.

The linear regression model has an MSE of 0.06, an RMSE of 0.2 and an MAE of 0.19, which indicates that the mean prediction error is relatively low. Furthermore,

Sampling type: 10-fold Cross validation

Scores

Model	MSE	RMSE	MAE	R2
LINEAR REGRESSION	0.06876586014125485	0.26223245440115694	0.19946152373923498	0.9312341398587451

Fig. 7. Prediction models performances.

the R2 of 0.93 suggests that the model explains about 93% of the variance in the data, indicating a good level of fit.

The coefficients of the regression model for the 28 public hospitals in Apulia are described in Fig. 8.

Data instances: 3
Features: 1
Meta attributes: 1

	name	coef
1	intercept	2.41838e-16
2	HOSPITAL ORGANIZATION	0.170574
3	PROPENSION HOSPITALIZATION	0.19381

Fig. 8. Regression model coefficients.

The dataset resulting from the analysis model proposed in the study, with the relevant predictive values generated by the linear regression, for the 28 public hospital facilities in the Apulia Region, is shown in Fig. 9.

Data instances: 28
Features: 2
Meta attributes: 3
Target: Numeric variable 'ENERGY COST'

	ENERGY COST	STRUCTURE NAME	LINEAR REGRESSION	Fold	HOSPITAL ORGANIZATION 0.894017	PROPENSION HOSPITALIZATION 0.923857
1	-0.745769	OSPEDALE OSTUNI	-0.665551	1	-1.86611	-1.78255
2	-0.460426	OSPEDALE FRANCAVILLA FONTANA	-0.583272	1	-1.6726	-1.52833
3	-0.378578	OSPEDALE CIVILE MARTINA FRANCA	-0.371675	1	-1.25215	-0.805925
4	-0.469693	OSPEDALE DELLA MURGIA - PERINEI	-0.365568	2	-0.851991	-1.1361
5	0.100588	OSPEDALE BARLETTA - 'MONS. R. DIMICCOLI'	-0.103025	2	-0.304612	-0.268841
6	-0.424145	OSPEDALE SCORRANO	-0.30743	2	-1.25587	-0.508038
7	0.29843	OSPEDALE ANDRIA - 'L. BONOMO'	-0.116555	3	-0.483352	-0.117045
8	1.6364	AO UNIV. 'OO RR FOGGIA'	1.91123	3	5.22458	5.05528
9	-0.502842	OSPEDALE CASARANO	-0.408186	3	-1.16271	-1.01687
10	0.761344	OSPEDALE BARI 'SAN PAOLO'	0.626752	4	1.83688	1.67788
11	-0.417241	OSPEDALE BISCEGLIE	-0.6698	4	-1.46354	-2.06907
12	-0.600637	OSPEDALE SAN SEVERO - TERESA MASSELLI	-0.45893	4	-1.24921	-1.22612
13	-0.687382	OSPEDALE MONOPOLI	-0.484848	5	-1.23629	-1.48059
14	0.151812	OSPEDALE BARI "DI VENERE" - TRIGGIANO	0.23771	5	0.213875	1.13649
15	3.22886	AO UNIV. CONS. POLICLINICO BARI	3.73946	5	10.0078	8.73097
16	-0.813643	OSPEDALE PUTIGNANO	-0.66868	6	-1.52997	-1.94286
17	-0.843701	OSPEDALE MANFREDONIA	-0.811186	6	-1.84558	-2.34117
18	1.35276	OSPEDALE LECCE - 'V FAZZI' (SAN CESARIO)	1.89555	6	3.32307	5.42516
19	-0.523552	OSPEDALE GALATINA 'S. CATERINA NOVELLA'	-0.667666	7	-1.35007	-2.06443
20	-0.522171	OSPEDALE MANDURIA 'GIANNUZZI'	-0.633389	7	-1.5107	-1.79218
21	-0.322481	OSPEDALE CASTELLANETA	-0.546519	7	-1.22505	-1.59083
22	-0.832146	IRCCS 'SAVERIO DE BELLIS'	-0.702665	8	-1.9766	-1.90177
23	-0.638146	OSPEDALE COPERTINO	-0.60114	8	-1.70254	-1.5926
24	1.92981	PRESIDIO OSPEDALERO CENTRALE TARANTO	1.13679	8	3.11079	3.55219
25	1.40147	OSPEDALE BRINDISI 'PERRINO'	1.18844	9	3.20641	3.40553
26	-0.70165	OSPEDALE CERIGNOLA 'G.TATARELLA'	-0.493111	9	-1.08998	-1.65949
27	-0.560034	ISTITUTO TUMORI GIOVANNI PAOLO II	-0.454713	10	-1.25174	-1.30056
28	-0.417241	OSPEDALE GALLIPOLI 'SACRO CUORE DI GESU'	-0.265152	10	-0.642778	-0.858102

Fig. 9. Hospital component scores.

In particular, the coefficient of the variable ‘Company organisation’ is 0.17. This means that an increase of one unit in the variable ‘Company organisation’ is associated

with an increase of approximately 0.17 units in the target variable 'Per capita expenditure on health energy'. Thus, an increase in business organisation (e.g. greater efficiency or better resource management) is associated with an increase in per capita expenditure on health energy.

Similarly, the coefficient of the variable 'propensity to hospitalise' is 0.19. This means that an increase of one unit in the variable "Propensity to hospitalise" is associated with an increase of about 0.19 units in the target variable "Per capita expenditure on health care energy". Thus, an increase in the propensity to hospitalise (e.g. an increased need for hospital care) is associated with an increase in per capita expenditure on health care energy.

The model intercept represents the value of the target variable 'Per capita expenditure on health energy' when all other variables in the model are zero. In practice, the intercept represents a kind of "expenditure floor" that the model predicts even in the absence of changes in the other independent variables.

Hospitals in their business complexity and their economic, social and environmental importance are large consumers of energy due to the continuous operation involving the use of complex electronic equipment to support clinical procedures.

A better management of healthcare resources in terms of a greater workforce, i.e. more hospital staff, rather than an increase in instrumental resources, beds and/or expansion of wards, which would contribute to an increase of an overall unit of the hospital corporate organisation, implies an increase in per capita healthcare expenditure on energy of 17%. From a managerial point of view, an assessment for a potential investment in corporate organisation would imply the same percentage increase for the energy cost item.

Analysing, at the same time, the hospital outcome factor counterbalancing the economic one, it can be seen that the relationship between the propensity to hospitalise patients and the relative increase in energy costs is quite robust. The final health outcomes understood as the reduction of discomfort, the prolongation of life, the decrease in the incidence of disease, rather than the satisfaction of users, family members, and the general population with the perceived overall quality and various aspects of care, are translated into the propensity to hospitalise patients. A propensity that is an expression of a need for care that sees its own unit increase associated with a 19% increase in the cost of energy.

A choice of resource allocation in the short/medium term can be optimised with the methodological approach proposed in this study, considering, on the one hand, the relationship between the hospital components and the cost of health care energy, but on the other taking note of the annual increase in the cost of health care energy per capita, which has increased in the three-year period 2020–2023, by about 142.65%, going to affect the regional health budget (AGENAS).

Observing the results of our linear regression analysis, represented graphically by means of the bar plot widget, by ASL and by hospital facility denomination (Fig. 10), it can be seen that the five regional public 2nd level facilities and two 1st level hospitals of ASL BA, have outliers with respect to the overall distribution of the regression values. These results are confirmed by the scatter plot (Fig. 11) distributing the predictive values by different type of level.

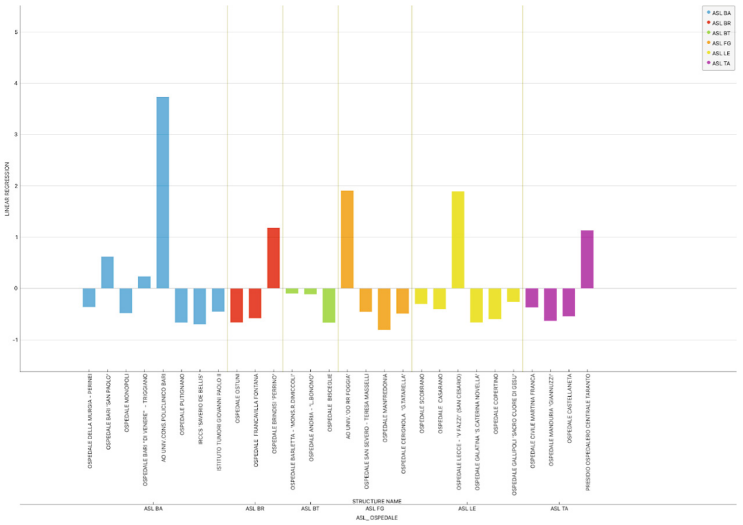

Fig. 10. Bar plot of linear regression predictive values.

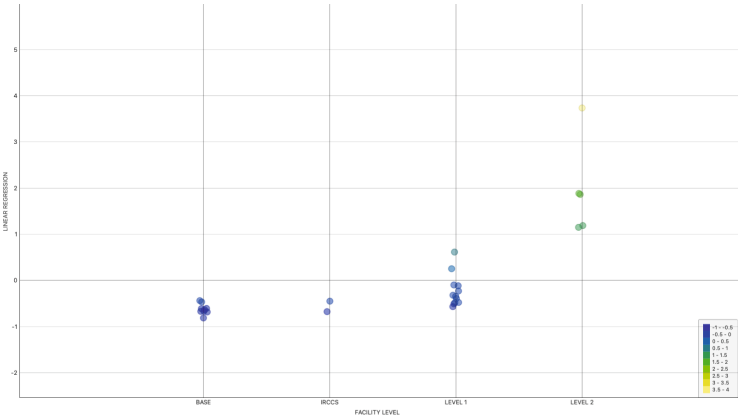

Fig. 11. Scatter plot of linear regression predictive values.

This assumption is confirmed by the ANOVA analysis applied to the same predictive regression values. With a p-value of < 0.005, the analysis confirms a significant difference between the different levels of the 28 public hospitals. As depicted in Fig. 12, there is a difference between the macro group consisting of basic, first level, and IRCCS hospitals compared to the second level hospitals.

The "LINEAR REGRESSION" column in Fig. 9 provides the estimated regression coefficients for each facility. For basic hospitals, IRCCSs, and level 1 hospitals, the estimated regression coefficients indicate that for a unit increase in hospital organization and patient admission propensity, there is an associated decrease in energy cost.

The opposite situation is verified for second level hospitals, in which an increase in hospital organization and an increase in the propensity to hospitalize will produce a higher energy cost.

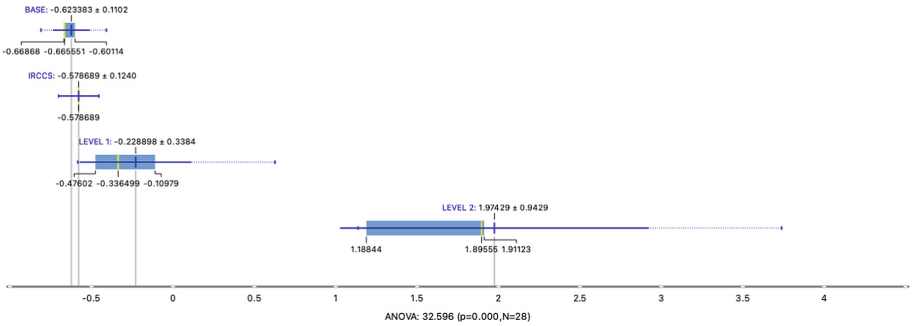

Fig. 12. Anova analysis applied to predictive regression values.

It is clear that there is no homogeneity in energy management practices among all hospitals. The management of healthcare companies should develop guidelines aimed at promoting a change in the organizational culture, by creating an energy consumption management plan following the ISO 50001 guidelines and prioritizing the acquisition of alternative or renewable energy. Additionally, they should focus on designing, constructing, and managing hospital buildings with a focus on energy efficiency and developing energy-related social responsibility programs (Borges de Oliveira et al., 2021).

The study found that an increase in organizational efficiency is associated with an increase in energy costs, while an increase in patient hospitalization rates is associated with an increase in energy costs. The analysis also highlighted some exceptions among hospital structures, with some showing a higher energy cost per capita than the average. The research suggests that better management of human resources could be more effective in reducing energy costs than purchasing new equipment or expanding structures. Furthermore, the study emphasized that energy costs have been increasing in recent years and that resource allocation choices must consider these rising costs.

Policies and decisions made by policymakers should aim to incentivize the public hospital network on the quality of services offered and not solely on economic productivity derived from DRGs, achieving a dual optimal allocation. An efficient allocation of economic resources that at the same time promotes an efficient redistribution of regional admissions offers optimal outcomes in terms of perceived quality.

5 Conclusion

There is no homogeneity in energy management among public hospitals, and better management of human resources could be more effective in reducing energy costs than purchasing new equipment and expanding structures.

The decision-makers, health professionals, and planners must understand, plan and specify the provision of medical care in terms of hospital capacity, availability, and supply.

The study proposes a future best practice for healthcare company decision-makers to have all the elements available, not only the company's own economic elements but also to take into account exogenous socio-economic factors. It also attempts to outline an integrated and unified vision to formulate coherent assessments of the entire regional hospital network in order to support the public decision-maker responsible for the regional healthcare system.

The study presented here has a limitation related to the calculation of the active mobility variable, as privacy legislation restricts access to the residence data of each patient, such as the exact address. For this reason, the route traveled by the patient to reach the hospital has been calculated as the straight line between the main city where the ASL is located and the municipality where the hospital is located. A planned follow-up is to integrate an analysis and representation system with a GIS to study hospital mobility with the actual distance traveled by patients, rather than relying on accessibility and variables related to the type and cost of transportation. This will provide a more accurate analysis of active healthcare mobility as an expression of the patient's choice of facility. Additionally, this approach will help to overcome the discrepancy between actual data availability for central hospitals that may combine several sites or connected hospitals that may be located in different and distant locations. Therefore, spatial variables relating to geographically dispersed facilities cannot currently be taken into account.

Regarding the usefulness of the proposed analysis tool, we propose developing what-if scenario analyses to simulate management decisions and resource allocation at the central regional level and at the local management level of individual hospital facilities, to verify the impacts and possible opportunities for improvement. This will involve an analysis by medical discipline, i.e., service offered, rather than using aggregate data. We also propose integrating the workflow proposed in this study with an analysis of DEA efficiency applied to hospital structures, using the main components identified as inputs and outputs.

Overall, the article suggests that policy-makers and healthcare organizations should aim to optimize the quality of services offered, not just the economic productivity derived from DRGs, in order to achieve an efficient allocation of economic resources and an efficient redistribution of regional admissions that offers optimal outcomes in terms of perceived quality.

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Comparing Environmental Values and CO2 Values in Geographical Contexts

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Abstract. The earth's surface, as is known, performs a number of functions, which guarantee the existence of flora, water, fauna, and further factors for the survival of nature. Among such functions, those generated on "the ground" and born from the balance of ecosystems stand out. In the past few years, the analysis of these functions has led to the classification of soils on the basis of the identification of a various "geographies" of "environmental values".

The subject of the paper is the story of the evolution of a recently started research. In this research phase the attempt is the try to compare different classification of soils.

The classification refer to identify sub-areas, constructed by evaluating scales of "environment value" and their ecological functions, by evaluating the carbon dioxide (CO2) containment capacity of the same environments.

The research of this paper therefore attempts to build a link between the first qualitative, spatial, multidimensional evaluation (the geography of environmental values that reminds us of the overlay) and the second monetary one, based on the containment capacity of CO2 emission compared to the ground.

The research was conducted on the basis of this comparison/overlapping, and the paper illustrates the results obtained.

The geographic rankings produced by the overlay between the mapping of eco-nomic values (related to the cost of segregated CO2) and ecological-environmental values (in the multidimensional geographic evaluation) should lead to a geographic-economic reapproach, which can alternate with forms of cross-evaluations between the cost-benefit analysis, compared through the use of overlay mapping (which reminds us "Design by Nature" Mc Harg).

At the same time, the variety of the surface and its sub-stratum is analyzed and in the field of environmental economics studies.

The aim is to identify the differences between various natural and possibly artificial soil surfaces by attributing an economic value to the different classes.

The concept of "Geography of Environmental Values" is recalled. The geographical classification is formed by building a "mosaic" of the different surfaces, which differ on a physical, ecological level.

These differences, found between those terrestrial factors that influence the dynamics of global warming, have already been reported in research and publications that use "monetization". The main issue to be analyzed regarding the diversity of surfaces (man-made and natural, protected and to be conserved), is an important topic in the field of geographical research aimed at constructing soil classifications.

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The identification of territorial differences through the scales of environmental values of the soils themselves can lead to hierarchies which, on the one hand, refer to indicators such as the ecological footprint, or impermeability, or biomass productivity, to which necessarily added the cost of carbon segregation, for the containment of global warming. The paper highlights the intersections between the qualitative classification of soils and the environmental value of the soils themselves, expressed through monetization, in the logic of implementing methods that contribute to improving the development of cost-benefit analyses.

Keywords: CO2 · Carbon sink · Environmental values · Spatial multicriteria analyses · Environmental Economics

1 Introduction

Our planet surface is the basis of deep studies whenever new needs appear in a future urban development, or new policies are oriented towards nature preservation.

The Earth's surface (as well-known) performs a number of functions, which guarantee the existence of flora, water, fauna and, as well, further oriented factors, on one hand in favor of survival of nature, and of preservation of natural way of life.

The first capital stage of planning activity is based on several addicted approaches for managing spatial, social, economic and environmental information.

The knowledge has to be increasing, in order to understand, to interpretate and to refer the investigation about natural attributes of soil, such as flora and fauna, heritage and landscapes.

Among such functions, we can take care (or in account) of those that have been generated on the ground, and have been born as a consequence of the balance of stand out ecosystems.

The paper recounts the developments of a research started a few years ago, when a group of scholars began to deepen the methods of analysis of territorial dynamics connected to the transformation of the environment generated by urban development. The first step concerned the application of the method that we can define as "spatial multi-criteria evaluation".

This research then continued in successive phases that are still ongoing. In these where the researchers have developed and applied methods for evaluating the environmental and economic effects in the natural and urban territory. The effects of such research produced a widening of studies linking the dimension of nature and soil with transformation and planning actions.

Evaluative approaches extended the investigation from multidimensional assessment to the search for "universal indicators".

At the same time some aspects of the study were considered of greater interest and the research was extended. One of the main themes today is connected to the relationship between geographical-territorial analysis and economic-environmental analysis.

The research seems an experiment, that appears aimed at improving new models of economic and environmental characterization and typification of parts of the territory.

The paper shows a tale about the evolution of some investigations that started few years ago, and that are still developing. Just more in detail, several current research phases are related with the attempt to apply paths and studies, in order to identify and classify a set of well-defined typologies of soil.

In the past years, the studies of such functions led to apply a new detection of soils in order to identify a variousness of "geographies of values": such spatial investigation has been consequently considered as the basis of multiple environmental ranking of values by sub-areas.

The analyses stats on the identification and the comparison of two approaches:

- the first approach is based on the definition of a set of values-scaling for environmental and ecological functions of soils
- the second approach is estimating the containment of carbon dioxide (CO2) inside the same environments.

The "geography of environmental values" therefore has been considered not a simple ranking, but an useful approach of classification of soils. As regards such experiment.

2 Assessing CO2 as Cost-Opportunities for New Land-Uses

The paper explains the approach of an investigation that is described in the following pages and, therefore, to create a link between a qualitative, spatial, multidimensional evaluation approach and a second quantitative monetary one, that is related with the amount of containment capacity of CO2 emission connected to the ground.

The research has already been conducted on the basis of this comparison/overlapping. Such paper therefore illustrates the results obtained.

The paper talks about the development of several researches, few years ago, carried out by groups of scholars began to deepen new methods of spatial analysis and interpretations of territorial dynamics connected with the environment changes due to the evolution of urban developments.

The new investigation concerned with new steps for implementing (as method) the "spatial multiple - criteria assessments".

Such research will continue in further phases that are still ongoing. As a consequence, scholars and researchers tried to test and apply those methods for evaluating the environmental and economic effects in the natural and urban territory.

The effects of investigation, in the wile, generated the increase of studies about the evaluation (in terms of dimensions) of soil and nature changes, due to planning procedures. Evaluation as well has been extended from multidimensional evaluation to the search for "universal indicators".

At the same time some aspects of the study were considered of greater interest and the research was extended.

One of the main themes today is connected to the relationship between geographical-territorial analysis and economic-environmental analysis.

The figure describing the overlay mapping shows different levels of the territorial representation with the identification for each map of the land cover (for example woods, artificial soils, crops, etc.). The elements of the grid that shapes the land covers are

associated with a given level of value connected to a territorial element according to a criterion. Land covers can be natural or man-made.

The overlapping of multiple layers sustains the combination of features that guide towards the result of a multiple criteria assessment. The multiple evaluation has been managed according some approach that is based on a cost-opportunities. The value of CO2 segregation represents a good way to define a ranking.

A priority starts when being considered on the base of capability of carbon dioxide. The

– the scale of values of each type of cover,
– the value of each land cover (that's related with scaling)

The overlapping of all the grids entails a resizing of each element of the grill, and in this way the spatial classification takes on a certain multidimensional character.

The consequent multiple dimensioned reality implies the use of a multi-criteria evaluation. The main task of the multiple criteria evaluation of natural, artificial land covers is based on providing information on the environmental value of the various territories that has been subjected to studies and research.

The geographic rankings produced by the overlay between the mapping of economic values (related to the cost of segregated CO2) and ecological-environmental values (in the multidimensional geographic evaluation) should lead to a geographic-economic reapproach, which can alternate forms of cross-evaluations between the cost-benefit analysis, after the implementation of overlay mapping (proposed by Mc Harg approach).

At the same time, the variety of the surface and its sub-stratum is analyzed and in the field of environmental economics studies.

The aim is to identify the differences between various natural and possibly artifi-cial soil surfaces by attributing an economic value to the different classes.

The concept of "Geography of Environmental Values" (proposed by G.Maciocco) recalls the implementation of multidimensional assessments and procedures in order to identify, by decision support systems, the most relevant parts of surface, according with.

The geographical classification is formed by building a "mosaic" of the different surfaces, which differ on a physical, ecological level.

Such discrimination found itself among those terrestrial factors that affect the dynamics of global warming. In the same time spatial analyses have already been reported in research and publications that put on appraisal for "monetization". The main issue to be analyzed regarding the diversity of surfaces (man-made and natural, protected and to be conserved), is an important topic in the field of geographical research aimed at constructing soil classifications.

The identification of differences and variousness - by the scales of environmental values of soils themselves - can lead to hierarchies which, on the one hand, refer to indicators such as the ecological footprint, or impermeability, imperviousness, biomass productivity. All such issues are necessarily conjoint with the cost of carbon segregation, for the containment of global warming.

The paper highlights the intersections between the qualitative classification of soils and the environmental value of the soils themselves, expressed through monetization, in the logic of implementing methods that contribute to improve cost-benefit analyses.

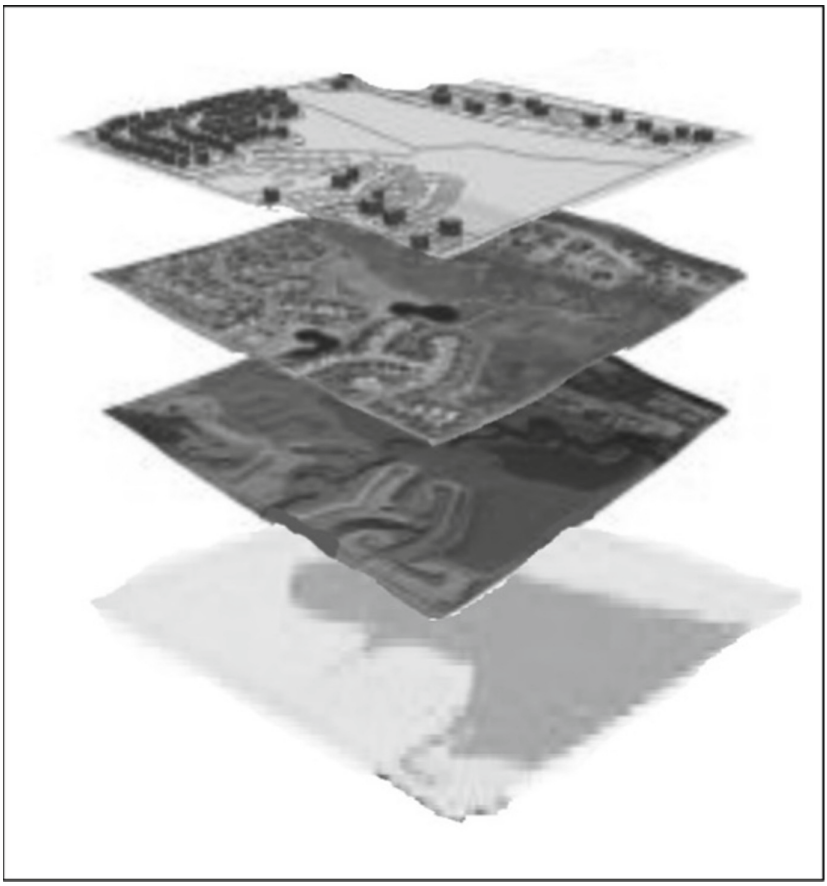

Fig. 1. The highest map is the result of an overlay of the three underponed maps

In Fig. 1 the procedure of "overlay mapping" is represented. The over-position of layers shows various representation and identification of each map of the land cover (for example woods, artificial soils, crops, etc.). Each maps represents a homogeneous component of "hearth surface". The highest map on the top is the result of three combination of layers. On the top the highest layer collects the various nature functions connected with each theme. Figure 2 represents by a grid the classification of multiple environmental values. Such values are the results of a multicriterial assessment. The result of the multi-criteria evaluation of land covers (natural, artificial) provides information on the deepest environmental features, linked with the various sub-environments that are subjected to studies and research.

The elements of the grid that shapes the land covers are associated with a given level of values, that are connected with a territorial element according to a criterion. Land covers can be considered as a mix among natural or man-made environments.

As regards the overlapping of multiple layers that recompose the ground, guides and forwards the combination of multiple criteria that identifies the scale of values of each type of cover.

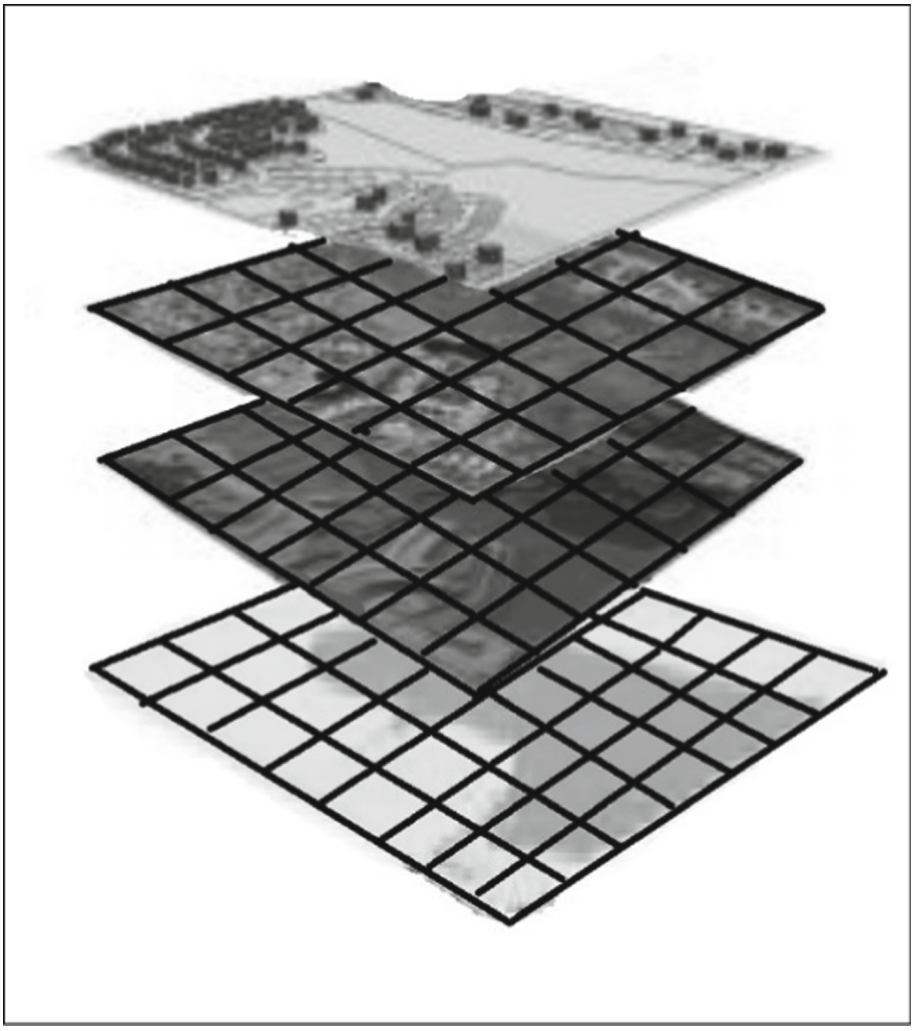

Fig. 2. The combination of grids favors the implementation of a spatial multiple criteria assessment. Each element of the grid represents an alternate piece. The table on the top is the basement of the multiple combination of layers

The value of each land cover becomes the overlapping of all the grids entails a resizing of each element of the grill. In this way the spatial classification takes on a certain multidimensional character. Multidimensionality implies the use of a multiple criteria evaluation. Each squared grid will represents the base for a criteria classification (connected by a layer) and each element of the grid represent a component of the layer.

3 Final Remarks

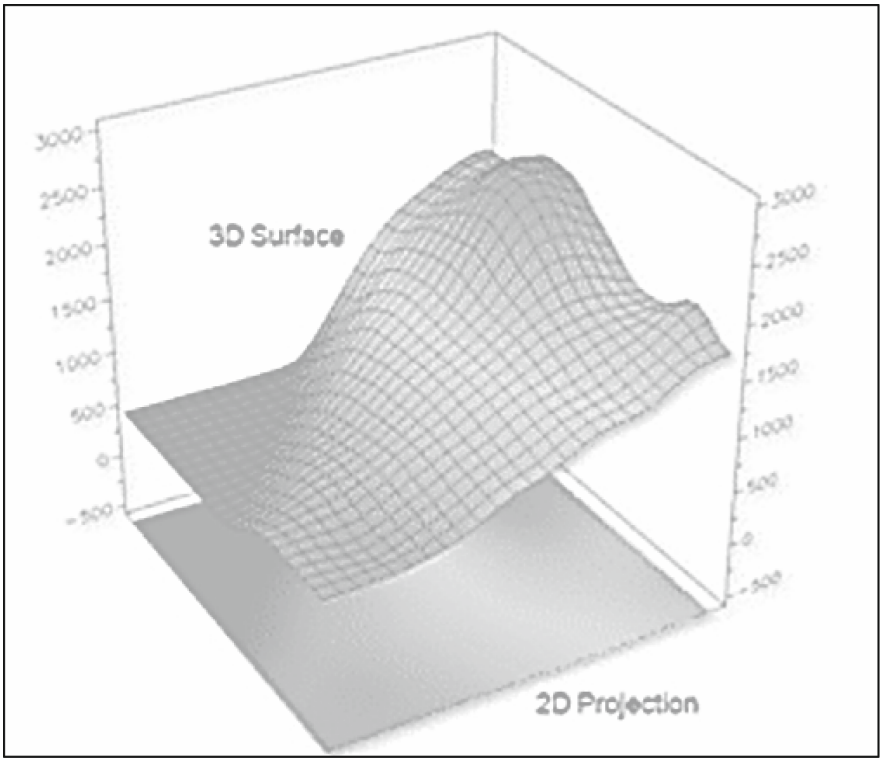

Fig. 3. Tre- dimension grids and assignment of values to each squared element.

4 Final Remarks

The triple dimension grids represent the assignment of values to each squared elements of soil. Such elements favor spatial multiple criteria assessment. First of all, the main element of the grid represents an alternate piece. The highest values represent a highest capability to CO2 retainment The table on the top is the basement of the multiple combination of layers. The height of the grid's surface represent the amount of money values proportioned with the capability to retain underground CO2.

The characteristics of layers represent the criterion for assessing the quality of grid element. First of all, it is important to not forget that the relevant attribution is the capability of retainment of CO2. Each element of the grid, can be considered an alternative solution. In the same time each layer represent a connected with the soil and the spatial units. Each square is represented as an element.

Figure 2, therefore, shows clearly that each square element of the grid can be characterized by a specifical money value, deriving from the capability of retain CO2. Figure 3 shows the variability of values, according to various circumstances.

As a consequence, a scaling of values is attributed to each element of the grid. In this case the assessment is not oriented to assign a score. The main attribute is the money value connected with the capability of retain CO2.

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Living Labs as a Method of Knowledge Value Transfer in a Natural Area

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Abstract. The Protected areas are clearly defined geographical spaces, recognised as such and dedicated to the long-term conservation of nature, with associated ecosystem services and cultural values. They provide environmental, social and economic benefits to society, which can be enjoyed at local, regional and international levels and support the Sustainable Development Goals (SDGs) [1].

In its first definition, according to the American model, a nature conservation area was understood as a different, exceptional site of uncontaminated nature, where human intervention was almost absent. The local community is excluded from land use because it is considered a threat to the preservation of natural ecosystems.

However, the success of these areas requires better collaboration with indigenous peoples, community groups and private initiatives, which are crucial.

However, these governance models must be participatory, because any conservation and promotion measures are more likely to fail without the education and direct involvement of different social actors.

The term Living Lab was introduced in the early 2000s to describe a user-centred research methodology to detect, validate and refine complex solutions in multiple and evolving real-life contexts. They were recognised as a dynamic multi-stakeholder network, that aims to stimulate and manage user-driven innovation in real-world contexts and to promote the interaction between technological and socio-economic forces.

This scenario allows the following research question to be formulated: "Can Living Labs represent a sustainable participatory model for sharing environmental, social and economic values in a natural area?".

In order to answer this question, a brief outline of the definition of Living Labs and the different approaches used will initially be provided. The methodology to be applied to natural areas for solving the management problems related to the complex heritage that characterise today's natural areas in general will then be illustrated.

Keywords: living labs · protected area · ecosystem services · innovation governance model · resilient rural area

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1 Introduction

The Protected areas are clearly defined geographical spaces, recognised as such and dedicated to the long-term conservation of nature, with associated ecosystem services and cultural values [2]. They provide environmental, social and economic benefits to society [3], which can be enjoyed at local, regional and international levels [4] and support the Sustainable Development Goals (SDGs) [1]. In its first definition, according to the American model, a nature conservation area was understood as a different, exceptional site of uncontaminated nature, where human intervention was almost absent. The local community is excluded from land use because it is considered a threat to the preservation of natural ecosystems [5–7].

However, the success of these areas requires better collaboration with indigenous peoples, community groups and private initiatives, which are crucial [8]. Over the years in Italy, the legislative orientation has changed from a vision of protection to one of protection and sustainable use, with the aim of conserving the natural environment (a path that began with National Law No 394/1991). In recent years, the majority of Italian parks have recorded a strong increase in tourist-recreational use, in accordance with the general expansion in demand for environmental tourism [9]. The increase in visitation (residents, national and international tourists) has induced a deepening crisis within these unique ecosystems, associated with population growth, increased consumption, climate change, increasing dependence on visitor revenue and growing demand for rural outdoor recreation [10].

All this has encouraged the development of a complex decision-making framework, characterised by a marked anthropocentrism and a continuous search for new management solutions and knowledge sharing. Therefore, there are conflicts in the use of a park's environmental resources that must be resolved to achieve environmentally compatible economic development [11]. Through good governance and effective management, the use and conservation of these areas can be ensured to meet the needs of current generations without compromising the possibilities of future generations [12]. However, these governance models must be participatory, because any conservation and promotion measures are more likely to fail without the education and direct involvement of different social actors [13].

Studies on Living Labs have been conducted by researchers for more than a decade [14, 15]. The existing literature addresses Living Labs not only as a topic that offers a wide range of research opportunities for creative scientists, but also as an innovative tool, methodology and design for stakeholders to address multiple challenges and needs in today's world [16]. The Living Lab concept first appeared in the 1990s. The term Living Lab was introduced by Prof. William Mitchell of the Massachusetts Institute of Technology in the early 2000s to describe a user-centred research methodology to detect, validate and refine complex solutions in multiple and evolving real-life contexts [17].

It was only in the 2000s that Living Labs were recognised as a dynamic multi-stakeholder network: a network that aims to stimulate and manage user-driven innovation in real-world contexts [18] and to promote the interaction between technological and socio-economic forces [19] . In Europe, Living Labs became established only in 2006 with the birth of the pan-European network ENoLL (European Network of Living Labs), consisting of 19 European Core Laboratories. ENoLL pursued the goal of addressing Europe's declining economic competitiveness and social challenges [20, 21].

In the following years, several state-level networks were also established e.g. in Belgium, the Netherlands, Spain, Portugal, Slovenia, the UK and also in Italy. Since 2010, ENoLL has opened its borders to non-European Living Labs, effectively becoming an intercontinental network and confirming itself as the largest association of LLs globally. Since their establishment, the Living Labs phenomenon has grown exponentially; in 2007 there were 19 such activities in Europe, while in 2022 the number exceeded 680.

This scenario allows the following research question to be formulated: "Can Living Labs represent a sustainable participatory model for sharing environmental, social and economic values in a natural area?"

Therefore, the main objective of this research is to present a possible approach to place Living Labs in the context of natural areas and to evaluate their possible contribution to their sustainable development. Indeed, the innovative Living Lab environment could be a key element of community and social change, as other experiences have shown, however in different (mainly urban) settings.

In order to answer this question, a brief outline of the definition of Living Labs and the different approaches used will initially be provided. The methodology to be applied to natural areas for solving the management problems related to the complex heritage that characterise today's natural areas in general will then be illustrated.

2 Development of the Living Lab Concept and Main Characteristics

As already mentioned, the Living Lab concept was born in 2000 [22, 23] , with the initial aim of testing new technologies in real-life context, initially familiar contexts.

In the course of their design, the Living Lab contest evolved [24] into an environment [25, 26], as well as a methodology [27–29] and thus, as a system [30].

Living Labs are, therefore, part of the broader category of real-world labs [31], in which other types of experimental approaches such as urban living labs, design labs, city labs, smart city initiatives, innovation hubs, community-based initiatives, social innovation labs and other specific experimental approaches can be found.

It is possible to find, around the concept of the Linving Lab, numerous practical applications as well as different research perspectives. For this reason, there is actually no single definition of Living Lab and several can be listed in the literature. It was deemed important to list some of them (Table 1), which are considered significant to highlight the evolution of the concept.

According to Molinari [37] a Living Lab can be considered as a multi-stakeholder platform "comprising different stakeholders, who perceive the same problem, realize their own respective interdependencies, and come together to agree on the best action strategies for solving it" [38].

Table 1. Main Living Lab definitions in literature (revised by [24]).

	Definition	Source
1.	*Living Lab represents a user-centric research **methodology** for sensing, prototyping, validating and refining complex solutions in multiple and evolving **real-life contexts***	first definition by Mitchell, W., J. Larson, K., and Pentland, A. at the Massachusetts Institute of Technology [23,32]
2.	*A user-driven **open innovation ecosystem** based on a business–citizens– government partnership which enables users to take an active part in the research, development and innovation process*	[33]
3.	*An organized set of **methods** and stakeholders, which focus on user involvement, user-centric research methodology for sensing, prototyping and validating solutions in evolving **real life contexts***	Vinnova (http://www.vinnova.se/sv/EU-internationell-samverkan/Nordiska-program-och-samarbeten/NORIA-net-Living-Labs---Nordiskt-baltiskt-samarbete-inom-IT/)
4.	*Consciously **constructed social environments** in which the uncontrollable dynamics of every day life are accepted as part of the innovation environment which enables designers and users to co-produce new products and services*	[34]
5.	*A user-centric research **methodology** for sensing, prototyping, validating and refining complex solutions in multiple and evolving **real life contexts***	[27]
6.	*Experimentation **environment** in which technology is given shape in **real-life contexts** and in which (end) users are considered co-producers*	[25]
7.	*Functional regions where stakeholders have formed a Public-Private-Partnership (PPP) of firms, public agencies, universities, institutes and people all collaborating for creation, prototyping, validating and testing of new services, products and **systems** in **real-life contexts**. Such contexts are cities, villages, rural areas and industrial plants*	[30]
8.	***Systemic innovation approach** in which all stakeholders in a product, service or application participate directly in the development process*	[35]
9.	***Home-like environment** by ambient intelligence and ubiquitous computing technologies such as wireless and sensor technologies to sense, prototype and validate **complex ICT solutions***	[36]
10.	*A user-centric **innovation milieu** built on every-day practice and research, with **an approach** that facilitates user influence in open and distributed innovation processes engaging all relevant partners in **real-life contexts**, aiming to **create sustainable values***	[24]
11.	*A design **research methodology** aimed at co-creating innovation through the involvement of aware users in **real-life setting***	[29]
12.	*Living Labs are open innovation ecosystems in **real-life environments** using **iterative feedback processes** throughout a **lifecycle approach** of an innovation to create **sustainable impact**. They focus on **co-creation, rapid prototyping & testing** and **scaling-up** innovations & businesses, providing (different types of) **joint-value** to the involved stakeholders. In this context, living labs operate as **intermediaries/orchestrators** among citizens, research organisations, companies and government agencies/levels.*	(https://enoll.org/about-us/what-are-living-labs/)(2023)

The main components of the Living Lab are shown in Fig. 1, which highlights aspects related to the multi-method approach, in which different users and stakeholders co-participate, to co-create ideas, projects, innovative strategies, by the help of Information and Communication Technologies (ICTs).



Fig. 1. Main components of Living Lab (author's elaboration)

The main characteristics recognised for Living Labs are as follows [30]:

- *Continuity:* allows for good collaboration, based on trust, which takes time to develop, but is important for strengthening creativity and innovation.
- *Openness*: is a fundamental principle in the innovation process, as it allows many points of view to be gathered, resulting in rapid progress. The open process allows the user-driven innovation process to be supported, wherever they are.
- *Realism*: it is necessary to create situations of use and behaviour of the specific context as close to reality as possible. The focus on real situations is relevant as it is what distinguishes Living Labs from other types of open co-creation environments (Second Life).
- *User empowerment*: it is important to motivate and empower users to engage in innovation processes, always based on the needs of the users. The efficiency of Living Labs is, in fact, based on the creative power of the user communities and their commitment in pursuing the objectives is crucial.

– *Spontaneity*: the collection of users' spontaneous reactions and ideas over time, as well as their processing and organisation, is very important for innovations to be successful [24].

From a conceptual perspective, today, there are four "types" of Living Labs:

- *Urban & Rural Living Labs*: city or rural area is a site for experimentation co-creation, active user engagement, real-life settings experimentation, multi-stakeholders, multi-method.
- *Research driven Living lab***:** they are research focused; this type of Living Labs are dealing with co-creating models for solving problems.
- *Living testbed:* this type of Living Lab focuses on the development of new technologies. (e.g. House/Farm of the future, Industry 4.0 labs).
- *Living Labs as a service:* this type of Living Labs offers, for SME's and start- ups, tools and methodologies to help them accelerate their innovation funnels.

Most Living Labs present today are, in effect, a combination of the four types described, with one of them becoming predominant.

In the specific context of natural areas, Living Labs could be considered as a tool that integrates local resource utilisation processes and could enhance the strengths for the future development of the areas considered. Thus, Living Labs in natural areas could be considered as an evolution of those created for rural areas, themselves developed by Smart Villages, which represent a model of sustainable villages. Through this model, bottom-up governance approaches can be used and ICTs solutions can be integrated into different services (such as e-health, e-mobility, e-government, e-education, e-commerce, agriculture 4.0, etc.) [39–42], enhancing the area's circular economy and ecosystem services of the natural area.

It is possible to find several examples of Living Labs on the web, in specific platforms (among all, the NEoLL) and also the literature offers a vast review of research carried out on Living Labs. In fact, most of the early initiatives on Living Lab approaches were mainly focused on urban areas. Over time, the Living Lab model adopted in urban areas evolved and was modified to be applicable to rural areas. Living Labs, on the other hand, are of little relevance in territorial areas characterised by natural areas, in any case partly man-made by local communities, where economic activities take place, some based on the use of natural resources and related ecosystem services.

A possible evolution could still enhance this model to be adapted to the realities prevailing in natural area. In particular, a Living Lab model area could contribute to the development of smarter, more inclusive and resilient and sustainable communities present in natural area, through the implementation of nature-based solutions, of projects for the valorisation of ecosystem services and the resources, co-created with and for local communities and stakeholders.

Based on experiences gained in Living Labs, in rural and also urban contexts, where the objective was the co-creation and sharing of sustainable and resilient innovations (CIHEAM Bari Mediterranean Innovation Rural Living Lab, Lunigiana Amica, ARCA LL, UNALAB, just to name a few on Living Labs - European Network of Living Labs [43], it is possible to hypothesise the main components that could characterise a Living

Lab model in natural area. In particular, they could be as follows: Governance, Natural context, Financing and business model, Nature and sustainable solutions, Users, Approach and method; ICTs support (Fig. 2).

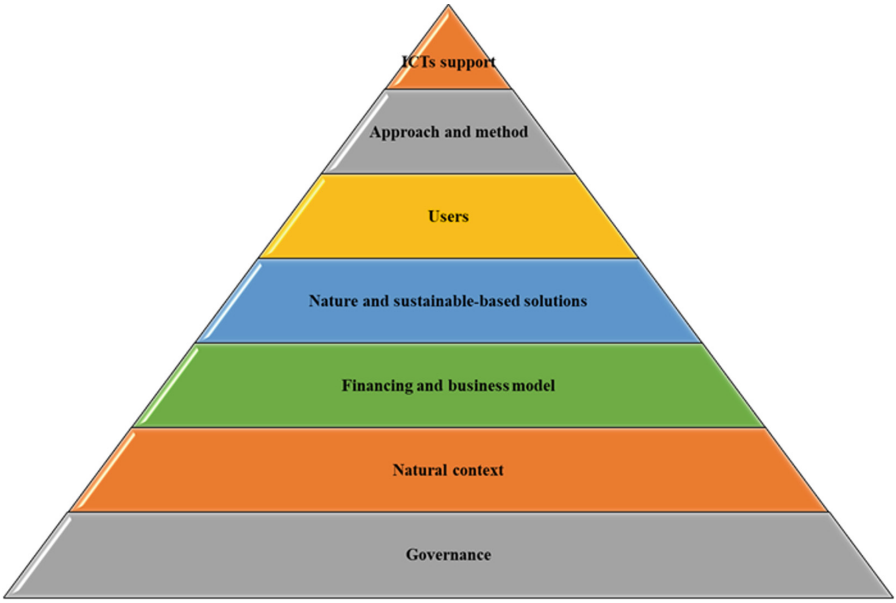

Fig. 2. Main components of Natural Living Lab (author's elaboration on [43]).

In natural areas, the Living Lab should enable the creation of a complex ecosystem, consisting of different actors, who act together to collaborate and co-create solutions to protect natural resources and related ecosystem services, on the one hand, and to develop the economic, social and environmental well-being of local and regional communities, on the other [38, 44].

3 A Possible Living Labs Model for Natural Areas

Globally, it is becoming increasingly important to ensure favorable living conditions and to adopt a sustainable approach in the development of natural areas. However, there are significant challenges to deal with, such as depopulation, lack of access to services and lack of innovation. For this reason, Living Labs are gaining importance as ecosystems built around local and regional needs, new technologies and participatory processes. To pursue the sustainable development goals established in the SDGs, it is important to use multidisciplinary knowledge and consider local contexts in the development process [45]. In this context, Living Labs for natural areas represent a concept that aims to create a holistic ecosystem in which various actors, such as inhabitants, entrepreneurs, policymakers, educators, farmers, and young leaders, work together based on sustainability values. The main purpose of Living Labs in natural areas is not only to maintain and

protect the environment but also to improve the economic, social, and environmental well-being of local and regional communities [44].

The innovation made by Living Labs in the context of natural areas, compared to other participatory approaches, is to focus explicitly on collaboration and involvement of the territory and its actors from the very beginning. In this way, the Living Lab turns out to be a real and virtual research environment, a context in which all actors can actively participate in the innovation process and in which all scenarios generated in the natural area can contribute to build smarter environments. The co-creation approach is essential for the design and implementation of successful products and services, especially when based on ICTs. Furthermore, if users are involved from the very beginning of the innovation process, the chances of developing services that truly meet their needs increase, as they can directly contribute with their opinions, ideas, behavior, and preferences [46].

If the objective of facilitation is to continuously involve all actors, a systematic mapping of those directly and indirectly involved helps to understand the different interests at the different stages and makes it possible to develop strategies to keep them motivated at all stages [47, 48]. It is important to systematically recruit stakeholders, and all interested parties to involve them in the collaborative planning of natural areas. Mapping all stakeholders helps to identify the necessary actors for the different stages around a central group, considering the variable involvement during the process [49].

The establishment of a Living Lab in a natural area could be articulated in several action plans to be implemented within the area, where culture, research and knowledge find a common place with the aim of promoting a sustainable tourism and development model. Within these action plans, it would be desirable to structure activities in environmental, social, economic, climate and landscape terms. In the context of these activities, the actors involved (resident citizens, tourist visitors both local and foreign, stakeholders in general, etc.) become an active part of a knowledge project, together with research organizations and institutions to implement a citizen science-oriented policy. Regarding the environment and landscape, it is planned to open the natural area to all interested parties as a place of culture on topics such as the protection and quality of landscapes, as well as the realization of environmental education programs in a natural setting, on topics such as air and water quality or anthropisation. In social terms, promoting the usability of natural areas is an important issue for the promotion of a healthy and sustainable lifestyle. Therefore, efforts should be directed towards making natural areas accessible in a safe and sustainable manner for all visitors. This can be achieved through the construction of infrastructure such as paths, cycle tracks and parking areas, the installation of information signs and the promotion of cultural and educational activities. Furthermore, it is important to make visitors aware of the need to respect the environment and adopt sustainable behaviour during their visit, such as respecting safety regulations, collecting waste and protecting the local flora and fauna.

The accessibility of natural areas not only promotes a healthy lifestyle, but also contributes to the preservation of biodiversity and ecosystem services and to supporting the economic activities of local communities. From an economic perspective, the tourism development of natural areas through a Living Lab can offer a unique opportunity to combine environmental and social sustainability with economic growth. The involvement of various actors, including residents, tour operators, government agencies,

environmental experts and others, can develop new solutions to promote tourism and enhance the area's natural resources. This can include the implementation of innovative technologies, the creation of ecological tourist routes, the promotion of local products and the organization of cultural and entertainment activities.

The Living Lab model is based on the concept of *Open Innovation*, in which the involvement of the users' community is fundamental, not only as observed subjects, but above all as sources of creation, true "drivers of change". In fact, information is collected directly from users in order to learn, immerse themselves in reality and propose sustainable development models for the natural area.

The Living Lab model proposed for a natural area is articulated in the following phases:

1) co-creation
2) research/exploration
3) experimentation
4) evaluation/monitoring

The Living Lab becomes a real and virtual research environment and, at the same time, an intelligent community in which all actors can actively participate in the innovation process and in which all scenarios of everyday life can be consulted and aimed at the development of innovative, shared services that meet users' needs.

The methodology proposed to implement Living Labs in the context of natural areas provides a barycentric action by the managing authority (park, province, etc.), which acts as a catalyst for the system of information from universities, territorial research centers (CNR, INGV, ISPRA, ecc.), environmental associations, and territorial institutions (municipalities, GAL, etc.). The information system as represented in Fig. 3 provides for the circularity of data and content between the actors involved to foster participation and the creation of sustainable development paths that includes the interaction of actors with different matrixes.

The active involvement of cultural associations in a Living Lab for natural areas is crucial to promote sustainability and conservation of local ecosystems. Collaboration between municipal authorities, local communities, businesses, and industry experts makes it possible to develop innovative solutions to manage natural resources more efficiently and sustainably, preserving the environment for future generations. The active participation of citizens allows for the acquisition of useful feedback to improve natural resource management policies and practices, as well as to promote environmental awareness and education. In this way, the Living Lab becomes a collaborative and inclusive space where the community can share knowledge, experience, and expertise to create shared solutions beneficial for all. The involvement of tour operators in a Living Lab for natural areas is crucial to promote sustainable and responsible tourism. Tour operators can offer their customers unique and authentic travel experiences, which contribute to the conservation of natural areas and the enhancement of the cultural heritage of local communities. The involvement of the Healthcare system in a Living Lab for natural areas is important to ensure the health and safety of visitors and local communities, promoting the physical and mental well-being of people and preserving the beauty and biodiversity of natural areas for future generations. Involvement of pension associations and schools in a Living Lab for natural areas is important to promote environmental education and

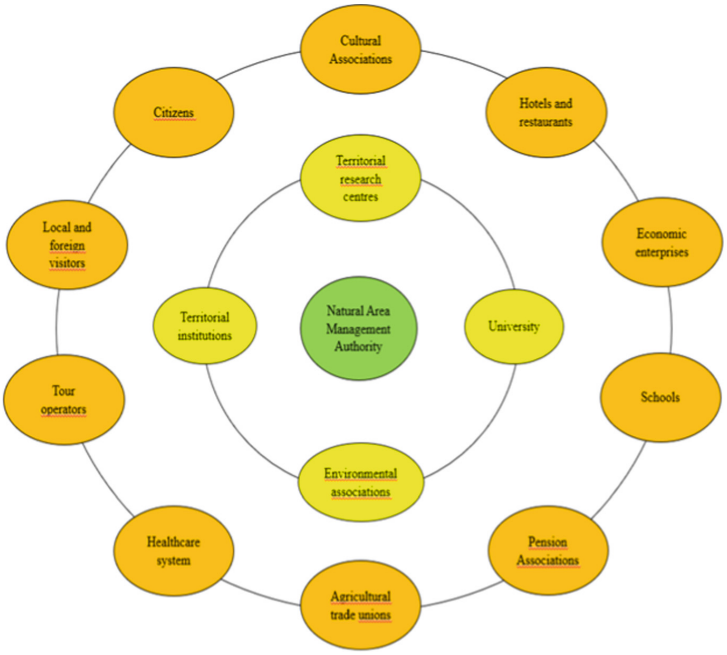

Fig. 3. Living Lab Operational Model Structure for Natural Areas (author's elaboration)

sustainability awareness among different segments of the population. This contributes to the formation of a culture of sustainability and the creation of a more environmentally aware and responsible society. Through the involvement of economic enterprises in a Living Lab for natural areas, it is promoted the development of a sustainable and inclusive local economy that creates job opportunities and value for local communities and preserves natural areas for future generations. The involvement of hotels and restaurants in a Living Lab for natural areas is important to enhance local culture and traditions. In this way, hotels and restaurants can offer their guests authentic and sustainable travel experiences, which contribute to the conservation of natural areas and the enhancement of local traditions.

Furthermore, an important element to consider should be the continuous monitoring and evaluation of the process itself, as Living Labs can fail due to user unsatisfaction or failure to implement innovations. The reasons for these failures often lie in the lack of monitoring and evaluation of the work and readjustment in the early stages [50].

4 Conclusion

Living Labs represent an important opportunity for the sustainable development of natural areas and the communities that inhabit them. Through their collaborative nature, Living Labs can involve all relevant actors and create synergies between them to develop innovative and sustainable solutions to specific problems in these areas. In particular, the focus on active participation of the local community and participatory planning are key

elements in ensuring the success of Living Labs. Indeed, systematic stakeholder mapping helps to understand the different interests in the various phases and enables the development of strategies to keep actors motivated and involved in all phases. Furthermore, the use of multidisciplinary knowledge and the promotion of sustainable development are further elements contributing to the success of Living Labs in wilderness areas.

A Living Lab in natural areas can include a wide range of sustainable solutions, such as the responsible management of natural resources, the promotion of sustainable tourism, the production of renewable energy, the collection and recycling of waste, the creation of sustainable agriculture and the promotion of local products. The testing of these sustainable solutions takes place through the involvement of actors at all stages of the process, from design to experimentation and the evaluation and dissemination of the solutions developed.

Living Labs have proven to be an important avenue to achieve the sustainable development goals set by the SDGs, as they enable knowledge networking between different actors and promote the circular economy and green growth. However, to optimize the benefits of Living Labs in natural areas, it is necessary to maintain a constant commitment to the active participation of the local community and to ensure the involvement of all actors concerned, including those less represented. This is the only way to ensure a sustainable future for natural areas and the communities that inhabit them.

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Refining the Use of Ecosystem Services to Increase Sustainability and Resilience in Tropical Agriculture

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Abstract. The humid tropics are highly suitable scenarios for exploiting ecosystem services for the sustainable management of agricultural lands. Accordingly, we hypothesized that the use of ecosystem services modifies the eco-physiological indices and soil organic carbon (SOC) accumulation. Therefore, the present study aimed to assess the eco-physiological indices and the content of SOC fractions by using different quality of leguminous biomass to compare the degree of energy optimisation and the possibility for SOC stabilisation/accumulation. The experiment was established in 2006 and four species of leguminous trees were used as biomass source, such that each plot received residues with different quality from combinations of the two legumes. The following treatments were performed: Leucaena + Clitoria; Leucaena + Gliricidia; Leucaena + Acacia; Gliricidia + Clitoria; Gliricidia + Acacia; and a control without legumes. Our results showed that eco-physiological indices were able to predict soil degradation by indicating whether organic C is accumulating to improve soil quality or whether the soil is being used exploitatively with declining C levels. They also showed that C accumulation in tropical agroecosystems depends on microbial growth favoured by a high-quality substrate. Even when low-quality biomass was used, the particulate fraction:mineral associated fraction ratio was almost always less than one, and recalcitrance seemed less important than microbial activity for C accumulation. In conclusion, tropical soil degradation can be avoided by ecosystem services such as: high-quality biomass production by nitrogen-fixing leguminous trees, efficient food-based web activities and recycled polyvalent cations for the build-up of stabilized organic-to-organic-complexes.

Keywords: Soil organic carbon · Soil Quality · Leguminous Biomass

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1 Introduction

Atmospheric carbon dioxide removal and offsetting the unavoidable non-renewable emissions in the global environment may also be a strategy for increasing soil organic carbon (SOC) and ensuring sustainability and climate change resilience on tropical farmlands [1, 2]. Globally, soil organic matter (SOM) contains more carbon (C) than that stored in vegetation and the atmosphere combined, or three times more C than in the atmosphere [3]. Thus, minor changes in the balance between inputs to and outputs from SOC would have a significant impact on atmospheric C and, therefore, soil can serve as a sink or source of C, depending on the strategy adopted for land use [4, 5]. As a result, effective climate change mitigation and agricultural adaptation strategies must be based mainly on processes that promote the stabilisation and accumulation of SOC [6].

Despite the difficulties in generating alternatives to shifting cultivation systems in the humid tropics, there are highly suited opportunities for using ecosystem services for sustainable farmlands management. Due to a combination of long periods of soil moisture with consistent year-round warm weather, the fast growth of nitrogen fixers, leguminous trees, and soil community decomposers can contribute decisively to the production and transformation of biomass in SOC [7]. Since SOC is the most closely correlated attribute to crop productivity and sustainability in tropical agriculture due to its effect on nutrient use efficiency, ecosystem services must be mainly directed towards improving the environment of the root zone [8].

Plant litter is the primary source of all SOM and stabilisation of plant-derived organic matter in soils. Therefore, steering the responses of the cycle of C towards SOC accumulation and climatic change attenuation is the challenge to be overcome for the next decades to achieve sustainability of tropical agriculture [9, 10].

Plant-derived organic matter in soils is primarily stabilised by two mechanisms: the formation of mineral-associated organic carbon (MAOC) and biochemical recalcitrance [11]. The latter is a controversial mechanism referring to complex molecules, such as lignin, which persists longer in the soil than simple molecules like glucose [12]. The first accounts for most of the stabilised SOC and has been increasingly recognised as the consequence of microbial growth and activity and as dependent on the proportion of C substrates used by microbes for their growth instead of being respired [13]. Thus, the efficiency of SOC stabilisation by mineral association will depend on microbial carbon use efficiency or how efficiently plant compounds are turned into microbial products to interact with available cation and soil minerals, increasing MAOC [14, 15].

Beyond the physical-chemical environment and the decomposer microorganism's community, the quality of the substrate is the principal factor that regulates microbial activities in the decomposition process [16]. Thus, since the ability of the substrate to be incorporated into microbial biomass is easier to change, the choice of quality of applied biomass via agroecosystem management has been used to drive the C cycle towards a higher level of stabilised SOC [17]. However, the results of the effect of litter quality on SOC stabilisation are inconsistent [18]. Indeed, if on one side, complex biomass biomolecules will not necessarily persist in the soil, on the other side, rich-N biomolecules are not necessarily decomposed and mineralized. Evidently, the effective management of soils as a C sink needs this uncertainty clarified, as it constrains the understanding of the link between substrate quality, microbial decomposition process,

and the build-up of stabilised SOM and C stocks [20]. The eco-physiological approach in soil microbiology introduced by [21] makes it possible to study this challenging question regarding the activity of the soil microbial community on substrate and SOC storage. The energetic metabolism balance of soil microbial communities has been a possible measurement of the capacity of microbial activities to contribute to storing SOC [22].

According to Odum's theory and extrapolated onto the microbial community, we should expect less community respiration with increasing below-ground species diversity in natural ecosystems [23]. In agricultural systems, where the quality and quantity of heterogeneous resource inputs can be partially controlled, there is an opportunity to increase microbial diversity, accelerating the maturity of the system [8]; this is especially true in the humid tropics, where the high risk of soil degradation can be offset by harnessing the ecosystem services provided by a diversity of efficient aboveground producers of biomass. Thus, the maturity of the system might avoid the detrimental effect of soil use intensification, increasing climate change resilience on tropical farmlands [24]. Accordingly, we hypothesise that the use of ecosystem services for producing different biomass-quality applied in the long-term modify the eco-physiological indices in tropical agricultural systems, and the measurement of these modifications can indicate the way to energy optimisation. Thus, knowing these processes, it would be possible to anticipate whether microbial community activity or service leads to lower or higher SOC content, evidencing the future agroecosystem sustainability degree and resilience status. The present study aimed to assess the eco-physiological indices and the content of SOC fractions of modified alley cropping systems with different quality of leguminous biomass to compare the degree of energy optimisation and the possibility for SOC stabilisation/accumulation.

2 Material and Methods

The experiment was installed in 2002 in the northern Amazonian periphery of Brazil. The region presents equatorial climate, hot and semi-humid with 1500 mm of an average annual precipitation and two well-defined seasons. A rainy season extending from January to June and a dry season with a marked water deficit from July to December. The local soil was classified as arenic hapludults, which consist of 240 g kg^{-1} coarse sand, 560 g kg^{-1} fine sand, 80 g kg^{-1} silt and 120 g kg^{-1} clay. Its chemical characteristics were as follows: pH ($CaCl_2$) 4.3, organic carbon (Walkley–Black) 9.3 g dm^{-3}, P 1.4 mg dm^{-3}, K 0.6 mmolc dm^{-3}, Ca 4.0 mmolc dm^{-3}, Mg 10.0 mmolc dm^{-3}, potential acidity (resin) 26.0 mmolc dm^{-3}, sum of bases 14.6 mmolc dm^{-3}, cation exchange capacity 40.6 mmolc dm^{-3}, base-saturation percentage 36 and bulk density 1.3 g cm^{-3}.

Soil liming was performed twice, once in January 2002 and once in 2007, by applying slaked lime at a rate of 1 Mg ha^{-1} to the surface (corresponding to 279 and 78 kg ha^{-1} Ca and Mg, respectively). In order to increase soil calcium content without change pH natural gypsum was applied in January 2017 at a rate of 6 Mg ha^{-1}, which corresponds to 1.010 kg/ha of Ca. Gypsum was grain size such that 95% by weight passed through a 0.25-mm screen mesh.

It was installed a modified alley cropping system (where trees are pruning and branches and leaves are applied in soil surface) included six treatments with four

replicates in a randomized block design. Four leguminous species were sow, including two that produce higher-quality residue (*Leucaena leucocephala* (Leucaena) and *Gliricidia sepium* (Gliricidia)) and two trees that produce lower-quality residue (*Clitoria fairchildiana* (Clitoria) and *Acacia mangium* (Acacia)) [25, 26]. The experiment was established in 2006 and four species of leguminous trees were used as biomass source, such that each plot received residues with different quality from combinations of the two legumes. The following treatments were performed: Leucaena + Clitoria (L + C); Leucaena + Gliricidia (L + G); Leucaena + Acacia (L + A); Gliricidia + Clitoria (G + C); Gliricidia + Acacia (G + A); and a control with bare soil (BS) and without legumes. In January of each year, maize (*Zea mays* L.) was sown with an inter-row spacing of 90 cm and an inter-plant spacing of 20 cm. Immediately, after planting the maize, the biomass produced from pruning the legumes was distributed homogeneously throughout the plots with the same treatments. The amounts of dry biomass that resulted from the leguminous plant combinations that were applied to the soil between 2008 and 2019 were quantified (Table 1). The plant biomass quality was assessed using the equation of Tian et al. [27] (Table 2).

Table 1. Amounts of the dry biomass of leguminous plants combinations (Mg ha^{-1}) applied to the soil since 2008 up to 2020, in a modified alley cropping system located in the Amazonian periphery of Brazil

Year	*Leucaena* + *Clitoria*	*Leucaena* + *Gliricidia*	*Leucaena* + *Acacia*	*Gliricidia* + *Acacia*	*Gliricidia* + *Clitoria*
2008	16.44	6.59	34.65	28.06	9.85
2009	10.50	10.60	22.60	20.40	9.50
2010	22.00	16.00	39.00	30.00	24.00
2011	11.05	7.48	27.20	22.87	6.72
2012	4.90	6.30	7.50	6.80	4.20
2013	7.80	8.90	12.50	13.20	9.20
2014	8.20	10.30	11.20	13.50	6.30
2015	10.10	8.20	11.20	13.50	10.50
2016	9.30	9.53	11.54	12.82	11.01
2017	9.82	8.90	10.92	13.14	9.54
2018	8.32	9.10	11.34	12.82	10.62
2019	8.92	9.02	12.04	13.06	10.30
Total	163.63	136.28	269.21	254.19	151.42

Table 2. Chemical composition and plant biomass quality index (PBQI) of the combinations of leguminous trees used

Treatments	C/N	Lignin (%)	Polyphenols (%)	PBQI
L + G	10.0	10.5	3.5	11.1
S + G	17.5	10.2	4.3	8.5
S + L	17.2	9.4	4.5	8.2
A + G	19.5	11.2	6.5	7.2
A + L	20.5	11.5	6.5	6.7

2.1 Soil Sampling

Soil sampling was carried out in 2020 to undertake the analyses of Ca, physical fractionation of soil organic matter and to determine the biological indicators of soil quality. The soil samples were collected with a probe-type auger in two dephts: 0–15 and 15–30 cm. A total of three single samples per plot were collected to obtain a composite sample. Part of the samples obtained were separated for biological analysis and kept under refrigeration until use. The other part of the samples was air-dried and passed through a 2 mm sieve before analysis.

2.2 Physical Fractionation of Organic Matter

The physical fractionation of soil organic matter was carried out according to the methodology proposed by Cambardella and Elliot [28]. Air-dried soil samples of 20 g were sieved through 2 mm mesh and weighed in 250 ml polyethylene cups, to which 80 ml of 5 g L^{-1} sodium hexametaphosphate was added. Each mixture was shaken for 15 h in a horizontal shaker, with 130 oscillations min^{-1}. After this process, the entire contents of each vial were placed into a 0.053 mm mesh sieve and washed with a weak jet of distilled water until the clay was completely removed. The material retained on the sieve was defined as total particulate organic matter (>53 μm) and was dried at 50 °C. After drying, each sample was ground in a porcelain mortar, after which an aliquot was collected, weighed and analysed for its C content, representing the soil particulate organic carbon (POC) in particulate organic matter, according to the Walkley-Black method. An aliquot of the 2 mm sieved subsample was ground in a porcelain mortar and weighed and analysed for the analysis of soil total organic carbon (TOC). Soil mineral-associated organic carbon (MAOC) was calculated as the difference between TOC and POC. The total organic carbon stock (TOCS) of each of the 0–15 cm layers was calculated by the following expression [29]:

$$TOCS = (MAOC \times \rho s \times E)/10 \quad (1)$$

where: TOCS = organic C stock at a given depth (Mg ha^{-1}), MAOC = mineral associated organic C content at the sampled depth (g kg^{-1}), ρs = soil bulk density (kg dm^{-3}), and E = thickness of the layer (15 cm).

2.3 Biological Indicators of Soil Quality

Metabolic Quotient (qCO2)
The metabolic quotient (qCO2) was determined by the Microbial Respiration/Microbial Biomass ratio, as proposed by Anderson and Domsch [30]. Soil basal respiration was determined according to the method proposed by Jenkinson and Powlson [31]. The carbon of the microbial biomass was determined by the irradiation-extration method, proposed by Islam and Weil [32] and adaptated by Mendonça and Matos [33]. 20 g of each soil sample were weighed in petri dishes, totaling six petri dishes per soil sample, three of which were submitted to irradiation in an Electrolux microwave oven model MTD30 (2,450 MHz) for three minutes and three remained non-irradiated. Subsequently, the samples were subjected to a rapid extraction, with K_2SO_4 0.5 mol L^{-1}, proceeding sequentially to carbon determination [34, 35]. Soil microbial biomass carbon (SMBC) was calculated by the equation

$$\mathrm{SMBC} = \mathrm{CI} - \mathrm{CNI}/\mathrm{kc} \tag{2}$$

where: SMBC = soil microbial biomass carbon in mg of C per kg of soil (or ug g^{-1}); CI = amount of C (mg kg^{-1}) recovered in the irradiated sample; CNI = amount of C (mg kg^{-1}) recovered in the non-irradiated sample; kc = correction factor that represents the efficiency of the extractor in extracting C from the soil microbial biomass (dimensionless), kc = 0.33 [36].

Microbial Quotient (qMIC)
The microbial quotient (qMIC) is an index used to provide indications on the quality of organic matter. The qMIC is expressed by the ratio between the C of the microbial biomass and the total organic C. To calculate this index, the results of the analyzes already described were used.

2.4 Soil Chemical Properties

Soil Ca was analyzed using an ion exchangeable resin, according to Van Raij and Quaggio [37]. Ca measurements were obtained using a Varian 720-ES ICP Optical Emission Matter Analysis Spectrometer. The accumulations of Ca, in kg ha^{-1}, in the 0–30 cm layer of the soil profile, were calculated according to the equation:

$$\mathrm{SCaA} = \mathrm{SEC} \times \rho s \times \mathrm{E} \times 10 \tag{3}$$

where: SCaA = Soil Ca accumulated in the 0–30 cm layer (kg ha^{-1}); SEC = soil element content (mg kg^{-1}); ρs = soil bulk density (Mg m^{-3}); and E = thickness of the layer (m). In order to obtain the SCaA in the treatments with biomass.

2.5 Statistical Analyzes

The results obtained were submitted to analysis of variance. Subsequently, the Tukey test was applied to compare the effect of the treatments on the dependents variables, at 5% probability. All statistical analyzes were performed using R, version 4.1.0 [38].

3 Results

Both metabolic coefficient (qCO2) and microbial quotient (qMic) were significantly affected by the quality of leguminous biomass applied. However, while qCO_2 was lower in the treatments with gliricidia (G), qMic was higher in those treatments than in other treatments with biomass. As such, in the 0–15 cm layer, qCO_2 was eight times lower in the treatment leucaena (L) with gliricidia (L + G) than in the treatments without G (Fig. 1). Surprisingly, in the treatment without leguminous biomass, qCO2 was lower than in other treatments except for the L + G treatment. In the same way, in the 15–30 cm layer, qCO2 was lower in the treatment with G and much lower in the L + G treatment other treatments with biomass. The higher qCO_2 was found in the treatments (A + L) and (S + L) in the 0–30 cm layer (Fig. 1).

In contrast, qMic was higher in the treatments with G, except for A + L, in the 0–15 cm layer. The qMic was more than twice as high in L + G than in A + L and S + L. In the 15–30 cm layer, qMic was more than twice as high in L + G compared to all the other treatments. Once again, among the treatments with biomass, the lower qMic was in (A + L) and (S + L) in the entire layer of 0–30 cm (Fig. 1).

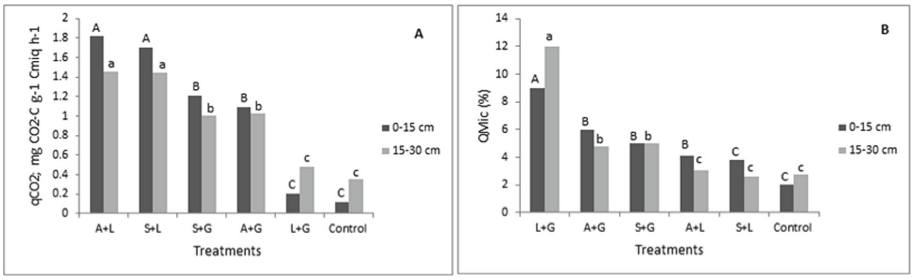

Fig. 1. Metabolic quotient (qCO_2) (A) and microbial quotient (qMic) (B). Columns with the same letters within each parameter do not differ by Tukey's test at 5% probability.

As for carbon-storing, both the SOC fractions were increased by the high-quality G biomass, mainly when combined with L. However, a larger contribution to the increase in TOC was provided by MAOC. Indeed, in the treatment, the L + G MAOC fraction was more than twice as higher as in other treatments in all 0–30 cm layers. Combining acacia (A) with L was less efficient in storing TOC compared to treatments with biomass. Surprisingly, even POC was higher in the L + G treatments than in treatments using lower-quality biomass (Fig. 2).

Total accumulated C in L + G (13,065 t ha-1) was almost the same as {(A + G) + (A + L) + (S + L) (13,787 t ha^{-1})}. According to Johannes [39], the TOC:clay ratio indicated that the soil is structurally degraded in the control area and A + L treatments, structurally median in S + L, good in S + G and A + G, and structurally very good in L + G. The Ca content was higher in the treatments with biomass than in the control area in the 0–30 cm layer. In L + G, it was higher than in the other plots with biomass and 31% higher than in the control area. Therefore, the Ca accumulated in L + G was 44% higher than in A + L (Table 3).

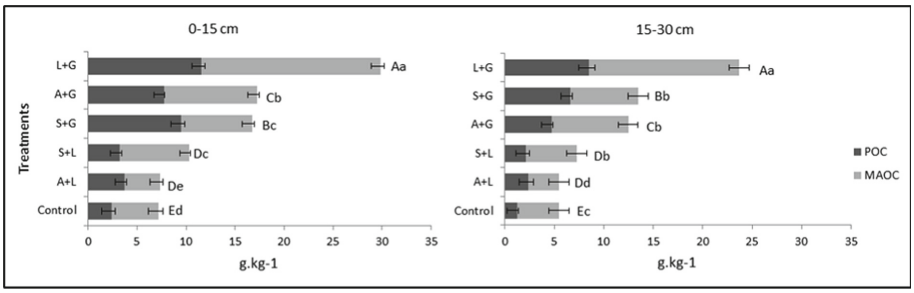

Fig. 2. Particulate organic carbon (POC) and mineral associated organic carbon (MAOC). Columns with the same letters (uppercase for POC and lowercase for MAOC) within each parameter do not differ by Tukey's test at 5% probability.

Table 3. Means of calcium contents, soil accumulated calcium (SACa), soil accumulated carbon (SAC), clay:TOC ratio and POC:MAOC ratio.

Treatments	Ca ($mmol_c\ dcm^{-3}$)		SACa ($t\ ha^{-1}$)	SAC ($t\ ha^{-1}$)	Clay:TOC	POC:MAOC	
	0–15 cm	15–30 cm	0–30 cm	0–30 cm	0–30 cm	0–15 cm	15–30 cm
L + G	61.5 a	59.5 a	1.77	13,065	1:5	0.6	0.6
S + G	58.9 b	56.3 b	1.42	5,470	1:8	1.3	1.0
S + L	59.8 b	55.1 b	1.40	4,778	1:12	0.8	1.0
A + G	58.1 b	57.4 b	1.38	6,717	1:8	0.8	0.6
A + L	56.8 b	55.2 b	1.23	3,539	1:18	0.5	0.3
Control	47.0 c	44.5 c	-	2,603	1:19	0.7	0.3

TOC – total organic carbon; POC – particulate organic carbon; MAOC- mineral-associated organic carbon.

4 Discussion

The variation in PBQI (from 6.7 in A + L, up to 11 in L + G) decisively affected the eco-physiological indices, the C utilization/accumulation and, consequently, the soil structure classification. According to Cotrufo [40], in a high-quality microbial substrate, as in the plots of L + G, some molecules can readily diffuse across the membrane, producing an additional resource for microbial growth. Therefore, the microbial anabolism:catabolism ratio is high, leading to more C production, which can be stabilised if polyvalent cations are available [41, 42]. The results of qCO2 in Fig. 1 showed that using low-quality biomass may not lead to higher C accumulated due to less energy optimisation of the microbial community under conditions of fast turnover, contrary to what common sense might suggest. Indeed, in a low-quality substrate or one rich in lignin and cellulose, as in A + L, the demand for resources is high, and the catabolism:metabolism ratio is low.

Thus, litter microbial biomass may be relatively low and fewer microbial residues are produced per amount of plant litter metabolised [43]. In addition, greater competition for few available C may favour bacteria-based food webs, which are less efficient in C assimilation than the more efficient fungal-based food webs [44].

Coherently with qCO2 results, the qMic increased when high-quality biomass was used. This quotient increases if organic carbon (C) accumulates in the soil and declines if the soil is used exploitatively [45]. Therefore, qMic was proposed by Powlson and Jenkinson [46] as a sensitive index of soil changes since microbial biomass responds more rapidly to soil changes than organic matter. This means that in the plots S + L, where the soil is in a structurally median stage, a degradation process could be ongoing and was primarily detected by microbial activities before degradation achieved the stage of A + L. In conclusion, both qCO_2 and qMic parameters showed to be potential tools for studying tropical agroecosystem performance forecasts, soil management effects, and sustainable alternatives for shifting cultivation. However, the values of these parameters in the control area suggest that they should be used together and never alone; otherwise, the small values of qCO_2 in the control area would tend to be interpreted as a positive soil attribute.

As expected, lower qCO_2 and higher qMic in treatments with G were followed by higher TOC contents, such as in the surface layer L + G, with PBQI equal to 11.1, where TOC was four times higher than in A + L with PBQI equal to 6.7 (29.9 g Kg^{-1} to 7.3 g Kg^{-1}). Although some authors like Witzgall et al. [47] and Lavallee et al. [48] have highlighted the essentiality of labile fractions for soil management for structurally fragile tropical soils as in this experiment, stabilised SOM fraction has been considered as the correlated closest attribute to soil rootability and maize productivity[8, 47]. The small values of the POC:MAOC ratio, almost always smaller than one even when low-quality of biomass was used, suggest that recalcitrance has had little importance for C accumulation in humid tropical conditions. This confirms the key role of ecosystem services provided by microorganisms, not just as promoters of C release to the atmosphere but also as promoters of SOC stocks through stabilising C into a not easily decomposed form [47]. The amount of C accumulated in L + G (13,065 t ha^{-1}) accredits this treatment as a C sink.

Recent studies [49, 50] have highlighted that the mechanisms through which SOC can be biologically stabilised depend on the capacity of the biomass added to increase the microbial necromass, which interacts with available polyvalent cations by incrustation and formation of organo-mineral complexes [42, 51]. In the present experiment, the low clay content of the soil and highly favourable climate conditions for biomass decomposition could also have harmed POC physic-chemical permanence or its intra-aggregates occlusion.

The higher Ca content in the treatments with G strengthens the hypothesis that interactions between microbial C and Ca are more important for maintaining Ca in the root zone than the recycling process [8, 42]. On the other hand, it is also clear that Ca availability is essential to take advantage of the increase in microbial C to construct adequate levels of MAOC [51]. Beyond avoiding Ca loss by leaching, Ca X SOC interactions contribute to the structural quality of soil, increasing MAOC. Thus, in L + G plots, the TOC:clay ratio was 1:5, very higher than the threshold of 1:8 established

by [39] for the optimal value of organic C for very good soil structure. Meanwhile, it was 1:18 in A + L TOC: clay ratio when the threshold for structurally degraded soil was 1:13.

5 Conclusion

Eco-physiological indices were able to predict soil degradation by indicating whether organic C is accumulating to improve soil quality or whether the soil is being used exploitatively with declining C levels. Our results also showed that C accumulation in tropical agroecosystems depends on microbial growth favoured by a high-quality substrate. Even when low-quality biomass was used, the particulate fraction:mineral associated fraction ratio was almost always less than one, and recalcitrance seemed less important than microbial activity for C accumulation in these circumstances. In conclusion, tropical soil degradation can be avoided by ecosystem services such as: high-quality biomass production by nitrogen-fixing leguminous trees, efficient food-based web activities to increase microbial biomass, and recycled polyvalent cations for the build-up of stabilized organic-to-organic-complexes.

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The Analysis of the Urban Open Spaces System for Resilient and Pleasant Historical Districts

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Abstract. Cities are the places where multiple challenges related to environmental, economic, social, and cultural phenomena are condensed. The increasing physical and systemic sensitivity/vulnerability of cities represents an opportunity to experiment with new models of urban development. Among these models, the scientific community is devoting particular attention to the use and the reuse of public spaces, especially in historical urban areas. What still lacks substance is the identification of which are the most suitable transformations to reorganize the urban spaces system according to its existing characteristics. Indeed, taking into account the intrinsic features of urban spaces means optimizing the benefits as well as cutting the costs associated with the necessary interventions.

This study proposes the analysis of the urban open spaces system – squares, green urban areas, gardens, paved areas, etc. – of seven historical districts in the city of Naples, according to their physical, functional, and accessibility characteristics. The aim is to define their structure and prevailing features in order to support decision-makers in the identification of appropriate and efficient adaptation, reorganization, and reuse measures. 13 indicators referred to 3 dimensions (Climate adaptation, Accessibility and equity, Urban quality) were aggregated into 3 composite indexes, through GIS elaborations, with the aim of identifying portions of territory where to primarily intervene, as well as the characteristics to be improved.

One of the main pieces of evidence of this study is that the suitability of urban spaces for adaptation measures cannot be separated from aspects like accessibility and pleasantness.

Keywords: Urban Resilience · Spatial Planning · Historical Districts · Urban Open Spaces

1 Introduction

Cities are the places where multiple challenges related to environmental, economic, social, and cultural phenomena are condensed [1, 2]. Firstly, climate change, due to global temperatures rising, increases the likelihood that extreme weather events will impact cities, compromising their physical integrity, organization, as well as public health and safety [3, 4]. Secondly, urban development (characterized by shrinking or

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sprawl phenomena) [5, 6], along with ever-faster societal/demographic changes [7, 8], impose the challenge of accessibility and equity, with the necessity of enabling access to urban services to disparate categories of people, especially the most fragile [9]. Finally, diffuse degradation, air pollution, and overcrowding, unless controlled, may undermine the quality and liveability of our cities [10, 11]. This non-exhaustive list of challenges contributes to the increasing physical and systemic vulnerability of urban areas. In historical city centres, the issue is even more thorny [12, 13], due to the consolidated urban structure and the presence of constraints that limit the transformation of the territory [14, 15]. Here, over the past decades, depopulation processes sparked urban decay and deterioration that have led to two different reactions: on one side, the establishment of immigrants and lower-income people, which transformed some historical areas (e.g., the next areas to central metro stations) into poverty and inequalities scenarios [16]; on the opposite side regeneration processes that, far from being a cure-all, led to gentrification dynamics that emphasized inequalities [17]. Beyond this, historical areas suffer problems that are the results of a stratified urban structure and a not-always planned urban fabric, such as the shortage of urban services, the lack of variegate facilities and economic activities [16] and, for what concern the focus of this study, the scarcity of green urban areas and the inadequacy of open public spaces [18].

Urban open spaces systems are intended as multipurpose infrastructures including different urban spaces (i.e., squares, green urban areas, gardens, paved areas), vital to urban resilience, as well as sustainability, health, safety, and well-being [19]. The inadequacy of the open spaces system of historical neighbourhoods, if, on the one hand, contributes to increasing physical and systemic vulnerability, on the other hand, represents an opportunity to enhance their resilience [18, 20] and, thus, experiment with new models of urban development.

Leveraging policies and planning practices that involve the open spaces system might well accelerate the adaptation of cities to the abovementioned changing environmental and social conditions [21]. And the benefits for historical districts might be even more. The scientific community is devoting particular attention to the use and the reuse of public spaces to cope with the impacts of climate change, social degradation, and inequalities [22, 23]. What still lacks substance is the identification of which are the most suitable transformations to reorganize the urban spaces system according to its existing characteristics and the territory's vulnerabilities and hazards. Indeed, taking into account the intrinsic features of the urban spaces system means optimizing the benefits as well as cutting the costs associated with the necessary interventions [24].

With these premises in mind, this paper proposes the analysis of the urban open spaces system of seven historical districts in the city of Naples, Italy, according to their physical, functional, and accessibility characteristics. In detail, the work includes characteristics of i) climate adaptation, considering the climatic zone of the city and its sensitivity to urban heat islands and water bombs; ii) accessibility and equity, considering the proximity to services and cultural facilities, along with the equable access of fragile people; iii) urban quality, considering urban design, value, and comfort. The aim is to define the structure and the prevailing features of the urban spaces system in order to support decision-makers in the identification of appropriate and efficient adaptation, reorganization, and reuse measures and the recognition of priority cases. The work was

carried out through the construction of 3 composite indexes in GIS, whose visualization options allow for the systemic interpretation of results. The objectives are: i) to verify if there is a correspondence between homogeneous characteristics and the reciprocal position of open spaces (in other words, if there is a systemic pattern); ii) to identify portions of territory where to primarily intervene; ii) to identify the characteristics to be improved. One of the main pieces of evidence of this study is that the suitability of urban open spaces for climate adaptation measures cannot be separated from social and quality/design aspects. The three dimensions go hand in hand since a good performance in one dimension cannot compensate for climate adaptation, equity, or quality deficiency.

This paper is organized as follows. The next section deepens the role of urban open spaces for cities' liveability and quality of life and the benefits that can be reached if pulled towards a systemic behaviour. Section 3 describes the utilized materials and the criteria to select the meaningful indicators, as well as the GIS-based methodology adopted to recollect the data and develop the descriptive indexes. Section 4 regards the application to the case study, including seven districts of the city of Naples having historical, architectural, and cultural value. Section 5 draws the conclusions of the work.

2 Advantages of an Efficient Urban Open Spaces System

The topic of urban open spaces has been widely studied in the literature. According to Tang and Wong [25], open spaces encompass different elements such as parks, gardens, recreational spaces, squares and undeveloped natural areas. Carr et al. [26] defined public open spaces as places where people can carry out their functional and leisure activities, creating a community. However, several studies deal with urban open spaces by defining them as a "system" [27–29], to the extent that they can work together to improve sustainability and resilience, being part of a network. According to numerous international organizations and scientific works, the urban open spaces system plays a key role in the definition of urban life, environment, and image [30, 31]. Indeed, an interconnected system of both green and public spaces provides a wide array of benefits related to environmental sustainability, air, and noise pollution decrease, groundwater management, land consumption, reduction of climatic risks, improvement of microclimatic conditions, and energy savings. In other words, the urban open spaces system is connected to a wide range of ecosystem services [32, 33].

For what concerns climate change, the right management and organization of urban open spaces system can be a significant tool in the hands of decision-makers, if addressed towards climate adaptation strategies [34]. Rising global temperatures and the consequent extreme weather events are causing severe impacts on urban areas, damaging basic services and infrastructure, and threatening human life, health, and housing [35]. Climate adaptation of urban open spaces (increase of green surfaces, permeable paved areas, nature-based solutions, etc.) constitutes a substantial part of the actions to be implemented to reduce these impacts and improve safety in urban areas [36]. To this end, it is necessary to know and classify open spaces according to their existing characteristics and systemic behaviour, and the territory's vulnerabilities and hazards. Diffuse and interconnected open spaces represent an opportunity to increase the climate resilience of urban areas [37], with benefits that range from the mitigation of heat island phenomena to the prevention of damages caused by storms/droughts cycles.

Thanks to its significant environmental, social, and economic value, the open spaces system is regarded as one of the most important components of sustainable development in cities [38]. After the Covid-19 outbreak, the benefits associated with public open spaces were further emphasized, as open spaces revealed themselves as essential places for promoting human health, social exchanges, and citizens' well-being [9, 39]. If easily accessible and connected, open spaces are able to influence people's quality of life since they indirectly encourage physical activity and subjective well-being, also constituting spaces of social aggregation that give value to the community's life [40, 41]. This is particularly important for fragile categories of the population, such as age-related categories (i.e., elderly and children) and socially and economically disadvantaged citizens (i.e., lower-income people and immigrants) [9]. For kids and older people, spending time outside is vital to their mental and physical well-being [30]. It reduces the chances of suffering from stress-related pathologies, anxiety, and depression, as well as the risk of cardiovascular disease, obesity, diabetes, and mortality among adults and of obesity and myopia in children [42]. Also, a diffused network of gardens, recreational, and gathering places can be the trigger point to promote passive recreation, social interactions, and inter-community contacts. This is particularly true for those citizens that suffer marginalization and deprivation due to poverty conditions or lack of integration in the community (e.g., foreigners). From an urban planning perspective, it follows the necessity of guaranteeing accessibility of open spaces, especially to these fragile categories.

In conclusion, the scientific community recognizes that green and high-quality the open spaces system provides a pleasant and comfortable environment where to live [43]. As a matter of fact, pleasant, well-lit, and cosy spaces contribute to the overall urban quality and guarantee a better perception of safety [44]. To a certain extent, their spatial structure and visual quality can impact directly and indirectly people's sense of wellness and satisfaction, impacting the way people gather and socialize in these spaces [45]. Three main factors are linked to the effective use of open spaces and the correct functioning of the open spaces system namely, users' needs, the quality of the physical features, and the spatial relationship with the context [44]. Understanding these three aspects is the keystone for a well-designed open space that attracts people, facilitates their activities, and encourages them to spend more time open air [46]. In particular cases, they contribute to defining urban identity and image, constituting a tool for city branding and promotion [47]. High-quality open spaces offer economic advantages since they are able to increase property values and neighbourhood attractiveness.

3 Materials and GIS-Based Methodology

3.1 The Dimensions of Urban Open Spaces System

The significance of urban places such as squares, green areas, built widenings, etc. in the development of transformation strategies and policies contextually oriented towards reducing vulnerability, increasing sustainability (including the energy one), and improving urban attractiveness and liveability has been continuing to rise and it requires the definition of appropriate techniques and tools to support local decision-makers.

Therefore, the main aim of the work described in these pages is to analyse the asset of the urban open spaces system in relation to some of the main current and near-future urban challenges. To this end, the method described in the section and the following ones was developed.

Through the lens of the systemic and integrated approach, characterising the urban areas that aim at reaching the previous goals, three main features were defined to assess the performance of open spaces, first. These three dimensions reflect the key role of open spaces system to facilitate the climate adaptation of urban areas, to improve their equitable accessibility to match the demand of nearby citizens (especially the most vulnerable ones) and to enhance the liveability and pleasantness of the urban built environment. The dimensions are:

- Climate adaptation;
- Accessibility and equity;
- Urban quality.

They can represent the three main criteria to satisfy when reorganising and improving the provision of open built and unbuilt spaces and the related pedestrian connectivity and ease of use of the related network. This is in line with the recent EU strategies that are oriented to stimulate the definition of valuable opportunities that can arise when cities re-think the use and the design of their open spaces system. As stated in the EEA [48], UN [49] and JRC [50] reports, the way open spaces in the city are laid out contributes strongly to affecting health, the perception of the urban context, especially in terms of pleasantness and safety, and to demonstrate the sensitivity of local administrators to issues of redevelopment, regeneration and adaptation of urban systems.

3.2 The Indicators

The three Climate adaptation, Accessibility and equity and Urban quality dimensions were measured through a set of indicators that reflect the main physical and urban context characteristics of the urban open space system. 13 indicators were selected based on their meaningfulness and the availability, accessibility, measurability and coverage of data (Table 1). Moreover, they allowed measuring the performance of urban open spaces system in terms of adaptation capacity (e.g. permeable surface of the soil that is relevant for both rainfall drainage and mitigating heat-wave effects), usability and proximity (e.g. suitability for vulnerable users such as the elderly), amenity (e.g. the value of the urban context due to the historical-architectural resources).

To make characteristics comparable and aggregable, the normalisation of indicators was necessary. The min-max method was used (1) as it is applicable to indicators with positive, negative or zero values and because it allows one to widen the variability of indicators lying within a small interval:

$$y_{Di} = \frac{x_{Di} - min(x_{Di})}{max(x_{Di}) - min(x_{Di})} \tag{1}$$

where D indicates the dimension and i the indicator.

The distances obtained from normalisation represent the absolute measurements of the gap between each element (the single open space) and the "ideal" one. The indicators that have a negative impact on the three dimensions were considered negative.

To measure the indicators, data were retrieved through processing in a GIS environment from open databases, such as ISTAT for population, Urban Atlas for land uses and Open Street Map for activities localization.

Table 1. The system of indicators.

Dimension	ID	Indicator
Climate Adaptation	01	Run-off coefficient
	02	Permeable surface
	03	Air temperature
	04	Tree coverage
Accessibility and equity	05	Distance from cultural services
	06	Distance from schools
	07	Foreign population pedestrian accessibility
	08	Elderly pedestrian accessibility
Urban quality	09	Historical, architectural and cultural value
	10	Real estate values
	11	Urban open space equipment
	12	Air pollution
	13	Noise pollution

3.3 Aggregation into the Three Dimensions Indexes

The normalised indicators were then aggregated into three main indexes. The literature states that there are several criteria for weighing and aggregating variables, ranging from ex-ante assignable weighting schemes to standards that determine the significance of indicators based on data analysis (e.g., through multivariate statistical analysis). This work did not define a system of weights since the paper represents a first approach to the research.

Hence, the average value of the indicators of each dimension was calculated so to obtain three indexes, one for each dimension (2). This operation is conceptually equivalent to putting all indicators on an equal footing.

$$\mathrm{I_{Dj}} = \frac{\mathrm{x_{Dj1}} + \mathrm{x_{Dj2}} + \ldots + \mathrm{x_{Djn}}}{\mathrm{n}} = \frac{\sum_{l=1}^{\mathrm{n}} \mathrm{x_{Dj}}}{\mathrm{n}} \tag{2}$$

While I_{Dj} indicates the index of the j dimension x_{Dj} is the normalised indicator of that dimension, n is the total number of indicators of the considered dimension.

The three aggregated indexes allow to assess the current functioning of the whole open space system about Climate adaptation, Accessibility and equity and Urban quality dimensions.

The outputs were then represented in GIS.

4 The Application

The proposed methodology was applicated to a part of the municipality of Naples, Italy. Naples is the third most populous city in Italy, with about 900,000 inhabitants and an average population density of 8,000 inhabitants on a surface of 118 sqkm. In particular, Naples historic centre is a unique example of architectural stratification through the centuries and is a vibrant catalyst of mixed activities. Along with these positive aspects there are many issues, such as the high population density and the strong rehabilitation needs of the built environment, including the cultural heritage (Fig. 1).



Fig. 1. Study area in the city of Naples, in Italy, embedding some historical districts.

The complexity of this local scenario of resources and challenges makes the area of Chaia, San Ferdinando, Montecalvario, San Giuseppe, Pendino, Porto, San Lorenzo an interesting study area, due also to their assorted characteristics in terms of urban fabrics, historical and architectural resources, activities distribution and geomorphological features, such as hilly conformation and coastal location.

Furthermore, defining the structure and relationships between the open spaces in this part of the city provides useful indications for assessing possible transformations to increase urban resilience and liveability.

Due to this heterogeneity, we expected that the open spaces located in some districts characterised by numerous urban redevelopment interventions would be more performing in come dimension, compared to the others located in districts where the attention dedicated to the supply and usability of urban places has decreased over time.

4.1 "Climate Adaptation" Dimension Index

Figure 2 shows the classification of open spaces according to the first Climate Adaptation synthetic index. It can be noted that Chiaia and San Ferdinando districts are mainly characterised by open spaces with medium and high normalised values of the index. These positive values, in terms of proper performance about climate vulnerability, can be related to the unified urban project of this part of the city where attention was dedicated to the ratio of full (buildings) to empty (spaces) in the urban fabric, by providing proper urban quality in terms of built and green open areas.

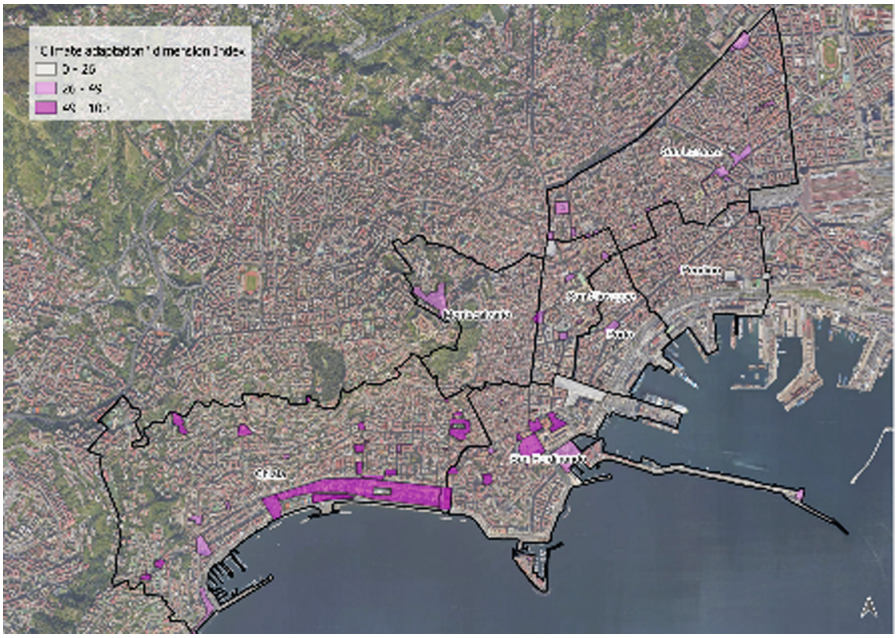

Fig. 2. "Climate adaptation" dimension index in the city of Naples.

The high historical and architectural value that characterises many of the open spaces of the San Giuseppe district and part of Montecalvario seems to be at the expense of their adaptability. The need to enhance and preserve places of such value clashes with the new requirements for water drainage and cooling, which call for adaptive measures

aimed at improving the eco-systemic capacities of these spaces, also affecting their reorganization.

Moving to the Porto, Pendino and San Lorenzo districts, here it is evident how the lack of attention to the quality of the urban environment and its maintenance lead to consequent criticalities both in terms of water runoff (absence of draining surfaces) and thermal comfort (absence of vegetation and therefore shaded surfaces). Some exceptions characterise San Lorenzo district thanks to the recent urban renovation interventions aimed at improving the tourist attractiveness of the relevant cultural and architectural heritage.

4.2 "Accessibility and Equity" Dimension Index

Figure 3 below displays the classification of open spaces according to the "Accessibility and equity" dimension index. It is worth noting that, differently from the climate adaptation index, here the open spaces that obtained the higher scores are the one in the ancient centre of the city (districts of Pendino, San Giuseppe, San Lorenzo, and Porto). What influences this result is the functional *mixité* of these districts and, in particular, the high density of cultural amenities like museums, exhibitions, theatres, and so on, and education facilities.



Fig. 3. "Accessibility and equity" dimension index in the city of Naples.

Other advantages consist in the variegated recreational and cultural offer and the typology of urban fabric, which can be referred to the structure of "walkable" cities, due

to the nature and historical development of this part of the city. The high accessibility for foreign population can be justified by higher percentage of foreigners in the central districts, more than in Chiaia and San Ferdinando.

Chiaia, according to the results, recorded lower levels of accessibility. This may be due to the morphological/orographic shape of the area along with the reciprocal position of open spaces. Who suffer from this distribution is the elderly because they could have greater physical impediments to reach these spaces.

4.3 "Urban Quality" Dimension Index

Figure 4 shows the "Urban quality" dimension index for the study area. We can observe a more homogeneous distribution, especially in the districts of Chiaia and San Ferdinando (higher scores) and Montecalvario, San Giuseppe and San Lorenzo (medium socres). Pendino and Porto still lag behind, because of scarce real estate value in the areas surrounding open spaces, the lack of urban furniture and higher levels of noise and air pollution.

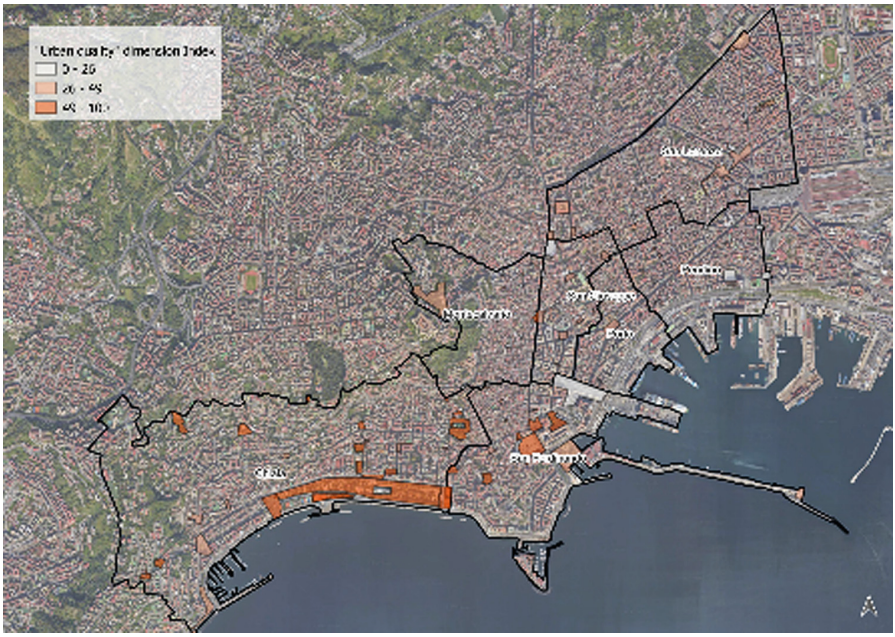

Fig. 4. "Urban quality" dimension index in the city of Naples.

5 Conclusions

"The key to a liveable city is related to the quality of urban life that takes place in its squares, places and streets" claim Lennard and Lennard [51]. This statement can be considered basic for this work, because of the many reflections that can be derived

from it for the governance of urban and territorial transformations. Enhancing inclusive and sustainable development of cities requires effective use of its resources. Thus, it is becoming increasingly important to maximize the utilization of available space. Many sustainable development principles can be implemented directly when building new neighbourhoods, but this is considerably more difficult in historic and consolidated districts where there are few opportunities for new construction. In order to provide its inhabitants with high-quality open spaces, a city should not only set aside enough space for it but also ensure that it is managed and maintained in such a way that it can be fully utilized. Public areas need to be secure, age-friendly, open to all, and inclusive in order to be fully utilized and, in this perspective, there is an effort to creatively utilize the open space system in order to maximize it. For instance, Barcelona is oriented to reroute traffic and building "superblocks," which are refurbished to include more open spaces and walkable paths. Other cities like Vancouver, Milan and Philadelphia have been investing in the green transformation of their urban places, using pro-environmental branding strategies and practices to make them more attractive and desirable places where living.

Given this scientific framework, it is worth analysing the structure of the urban open space system according to its climate vulnerability, usability and liveability components. In order to achieve this objective, we developed a simple methodology to assess the performance of the open spaces related to these three main dimensions, by providing a first cognitive result for the study area located in the central part of the city of Naples. To this aim, 13 indicators were defined and they were then aggregated into three synthetic indexes useful to obtain an overall assessment of the urban open spaces system. The result was a classification of the open spaces according to the Climate Adaptation, Accessibility and equity and Urban quality indexes that can be visualised on digital maps, enabling a comparison of the historical districts under study.

For the application of the proposed method, we chose the central area of the municipality of Naples in Italy, which is characterised by the high heterogeneity of its districts in terms of resources, vocations and sustainable development. We found a great disparity between the central eastern and western districts. Specifically, while the former resulted to have better levels of accessibility and equity, the latter had better results in the fields of climate adaptation and urban quality. This situation is indicative of a diffused decay of the open spaces network in the ancient centre. The high walkability and accessibility of these districts is not enough to make the open spaces a point in favour of the population living there.

The aim of this was to support decision-makers in improving the resilience and attractiveness of the urban open spaces system, to contribute to increasing citizens' quality of life. In this sense, it represents the first step of a wider research work on the subject that will focus on the sustainable transformation and climate adaptation of urban open spaces system.

Future developments of the research will regard the structure of the methodology, especially for what concerns the techniques to classify open spaces and to weigh their main characteristics, according to the proposed dimensions. Furthermore, another application to a different city may confirm the replicability of the Index also for other contexts.

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Monitoring Recent Afforestation Interventions as Relevant Issue for Urban Planning

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Abstract. In the UN Decade on restoration, urban and peri-urban areas are increasingly recognized as key to implement afforestation interventions, thus contributing to supporting ecosystem services provision.

Nevertheless, the relation between the current vegetation health and typologies of Land Use/Land Cover (LULC) and related changes is still poorly explored, thus affecting ecosystem planning. Therefore, this study aims to investigate, through the employment of Normalized Difference Vegetation Index (NDVI), the vegetations' health in i) unchanged forest ii) afforested areas - considering the different LULC classes in which afforestation occurred iii) unchanged LULC classes in the surrounding of afforested areas; in the case study area of the Metropolitan City of Milan.

We first analyze the LULC transformation aimed at identifying unchanged forest (1954–2018), recent afforested areas (2012–2018), and the unchanged LULC surrounding the afforested areas (2012–2018) i.e., being the same LULC that preceded the afforestation process. We then analyzed Sentinel-2 NDVI sequences (2017–2023) in these three LULC transformation/unchanged categories, respectively.

The results show lower NDVI values in afforested areas transformed from impervious soil and arable lands into forest. Moreover, the results of the Wilcoxon test indicate that the average NDVI values of recently afforested areas from impervious soil, arable lands and pastures are statistically different from those of unchanged forest.

Results can be used to set an environmental benchmark for afforestation processes providing a basis in the selection of future planning priorities.

Keywords: Restoration Ecology · Land Use/Land Cover Change · Ecosystem services

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1 Increasing Importance of Afforestation Intervention in Urban and Peri-Urban Environments

Arresting and reversing the ecosystem degradation and loss of biodiversity, under the United Nation Decade on Ecosystem restoration 2021–2030, is an overarching worldwide goal [1]. At EU scale, the commitment to reach this goal was strengthened by the EU Green deal [2], EU Biodiversity strategy for 2030 [3] and, more recently, the EC proposal for a Nature restoration law [4]. Within this framework, the restoration ecology as "the process assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" [5] increases the overall resilience of the urban and peri-urban areas, also limiting adverse impacts of climate change in cities [6]. More specifically, the active restoration through e.g., the implementation of afforestation interventions [7], if planned and designed considering the ecosystems complexity and diversity [8], lead to restore ecosystems enhancing the related services, such as biodiversity, carbon storage and sequestration [9], heat and urban flood risk mitigation [10, 11], thus contributing to reduce the vulnerability of communities against climate risks [12]. In an effort to improve such benefits, the mapping and assessment of the Ecosystem Services (ES) provision related to different Land Use/Land Cover (LULC) is crucial as LULC affects e.g., the quality of habitats [13], and the LULC transformation impacts on different ecosystem services provision [14]. The afforestation process is one of the major LULC transformations worldwide [15] and policies and programs, as already mentioned, are supporting such interventions globally for increasing the ES provision and improving the biodiversity and the quality of habitat. However, monitoring such afforestation interventions within the overall umbrella of active restoration is key, since it is commonly assumed that afforestation should tend to have the same dynamics and complexity as natural ecosystems to be considered successful [14] and the incomplete recovery is often due to scarce understanding of the LULC and its transformation [16]. So far, several researchers analyzed the combination of spatial change of LULC and Normalized Difference Vegetation Index (NDVI) time series to assess e.g. the modification of vegetation cover and its implication for degradation monitoring in semi-arid environments [17, 18] or the negative impact of urban development on natural ecosystems [19]. NDVI is a key indicator usually employed to assess a wide range of ES including the habitat-supporting services (according to the Millennium Ecosystem Assessment (2005) classification [20]) [21, 22].

However, the relevance of the type of LULC on which the afforestation intervention has placed and the current vegetation health of such afforestation intervention is still poorly explored resulting in limited information to support urban planning in selecting the priorities of intervention in the next future. Thus, within these limits, further efforts are needed to monitor the current, and better target the future, afforestation interventions in urban and peri-urban areas aiming at increase related ecosystem services provision.

Based on the above-mentioned issues, this study aims at analyzing the vegetation heath of forest and recent afforestation interventions occurred in the Metropolitan City of Milan comparing the NDVI values, as proxy of vegetation's health status, considering in particular: i) unchanged forest as reference state (1954–2018); ii) recent afforested areas from different LULC (2012–2018); ii) unchanged LULC in the surroundings of afforested areas (2012–2018).

2 Materials and Methods

2.1 Case Study Area

The Metropolitan City of Milan (MCM) is located in Lombardy region, covers about 157,565 ha and is mainly dominated by arable lands (68,291 ha) and impervious soil[1] (55,525 ha). Artificial, non-agricultural vegetated areas (9,322 ha), pastures (7,123 ha), shrublands and open spaces with little or no vegetation (2,531 ha) and forest (10,308 ha) as well as wetlands (108 ha) are scattered throughout the plain, fertile land. Larger wooded lands, dominated by broadleaf forest, are mainly located in the Ticino riparian zone and in the north and north-west part of the MCM (Fig. 1).

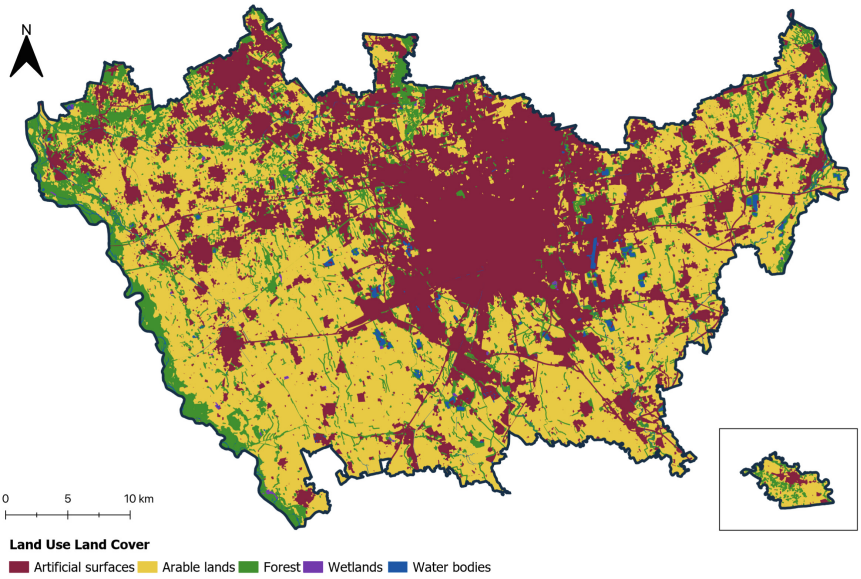

Fig. 1. Map of the main LULC classes in MCM in 2018. Data elaborated from DUSAF (Destinazione d'Uso dei Suoli Agricoli e Forestali) database, ERSAF Lombardy region (https://www.geoportale.regione.lombardia.it/).

2.2 Land Use/Land Cover Change Classification

We first reclassify LULC of MCM into categories of interest for this study. Through the Geoportal of Lombardy region[2], the Land Use/Land Cover database (DUSAF) was downloaded and used as input to identify:

i) unchanged forest (1954–2018);

[1] In the present article we define as impervious soil the areas belonging to the classes 1.1, 1.2, 1.3 of CORINE Land Cover, within the macro-class "1. Artificial surfaces", to differentiate these to the class "1.4 Artificial, non-agricultural vegetated areas".

[2] https://www.geoportale.regione.lombardia.it/.

ii) recent afforested areas, i.e., areas transformed from other LULC (2012) to forest (2018);
iii) unchanged LULC - non-afforested areas, i.e., areas in the surroundings of afforested areas that have not changed LULC (2012–2018).

The Land Use/Land Cover dataset (DUSAF) is freely downloadable and available for the years 1954, 1980, 1999, 2007 and 2018 and the first three levels of LULC classification are consistent with the EU Copernicus CORINE Land Cover legend[3].

The vector data for the reference years 1954, 2012, 2018 were first converted into a raster with a resolution of 5m. Each pixel was then reclassified according to Table 1. In particular, three main types of areas were identified:

i) unchanged forest (called FOR-FOR in Table 1): forest in both years 1954 and 2018. To reduce the number of classes, broad-leaved and mixed forests were joined, no coniferous forest was identified in MCM;

   FOR-FOR class was used as reference state to assess differences in values between historic ecosystems (i.e. unchanged forest) [23], and recent afforested areas;
ii) recent afforested areas (namely IMP-FOR, UGA-FOR, ARA-FOR, PRM-FOR, PAS-FOR and SHR-FOR in Table 1): other LULC classes in 2012 that belonged to forest in 2018. Areas converted from wetlands (class 4) and water bodies (class 5) were not considered in the present study due to their very small coverage comparing to the whole MCM;
iii) unchanged LULC - non-afforested areas, i.e., other LULC within 1 km distance from the recent afforested areas whose, in contrast to the latter, maintained the same LULC in 2012 and 2018 (called IMP-IMP, UGA-UGA, ARA-ARA, PRM-PRM, PAS-PAS, SHR-SHR in Table 1). These areas were used to assess the differences, if any, between the afforested areas and their surroundings.

We re-classified the dataset obtaining a single-band raster whose pixel's value corresponds to every detected change. The raster image was then converted into a shapefile containing a polygon for each group of adjacent pixels belonging to the same type of LULC change class. Resulting polygons smaller than 0.1 hectares have then been removed from the datasets, since they may have been artifacts resulted from rasterization and inconsistencies of photo-interpretation between different years.

2.3 Computation of NDVI

In previous studies, indicators calculated from surface reflectance values obtained from satellite measurements have been successfully used to assess and monitor vegetation health [24–26]. The use of satellite imagery has the advantage of covering large areas with continuous monitoring, which would be costly with in-situ measurements. To assess significant differences between unchanged forest, recently afforested areas and different types of unchanged LULC in the surrounding of afforested areas, we used the NDVI

[3] https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/html.

Table 1. Reclassification of Land Use/Land Cover (LULC) considering: i) unchanged forests (1954–2018), ii) afforested areas (2012–2018) and iii) unchanged LULC – non-afforested areas (2012–2018). Per each type of classification, the LULC classes in 1954, 2012 and 2018 (for further information about classes please see https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/html), the related Type of conversion from a LULC to another and the Abbreviation are reported.

Unchanged forest (1954–2018)			
LULC class in 1954	**LULC class in 2018**	**Type of conversion**	**Abbreviation**
311, 312, 313	311, 312, 313	From "Forest" to "Forest"	FOR-FOR
Afforested areas (2012–2018)			
LULC class in 2012	**LULC class in 2018**	**Type of conversion**	**Abbreviation**
11, 12, 13	311, 312, 313	From "Impervious soil" to "Forest"	IMP-FOR
14	311, 312, 313	From "Artificial, non-agricultural vegetated areas" to "Forest"	UGA-FOR
21	311, 312, 313	From "Arable lands" to "Forest"	ARA-FOR
22	311, 312, 313	From "Permanent crops" to "Forest"	PRM-FOR
23	311, 312, 313	From "Pastures" to "Forest"	PAS-FOR
32, 33	311, 312, 313	From "Shrublands and open spaces with little or no vegetation" to "Forest"	SHR-FOR
Unchanged LULC – non-afforested areas (2012–2018)			
LULC class in 2012	**LULC class in 2018**	**Type of conversion**	**Abbreviation**
11, 12, 13	11, 12, 13	From "Impervious soil" to "Impervious soil"	IMP-IMP
14	14	From "Artificial, non-agricultural vegetated areas" to "Artificial, non-agricultural vegetated areas"	UGA-UGA
21	21	From "Arable lands" to "Arable lands"	ARA-ARA
22	22	From "Permanent crops" to "Permanent crops"	PRM-PRM
23	23	From "Pastures" to "Pastures"	PAS-PAS

(*continued*)

Table 1. (*continued*)

32, 33	32, 33	From "Shrublands and open spaces with little or no vegetation" to "Shrublands and open spaces with little or no vegetation"	SHR-SHR

[27] (Formula (1)).

$$NDVI = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}} \quad (1)$$

where NIR is the reflection in the near-infrared spectrum and RED is the reflection in the red range of the visible spectrum. The NDVI is employed for examining the vitality of plants by capturing the amount of light absorbed and reflected by available chlorophyll [28]. The value range of the NDVI is -1 to $+1$. NDVI negative values correspond to water; values close to 0 are typical of barren soils or vegetation at the beginning and the end of the growing season; low positive values correspond to shrub and grassland and high values correspond to temperate and tropical rainforests with highest greenness [24].

NDVI values were computed by Sentinel 2 multispectral imagery collections with high spatial and temporal resolution (10m images related to bands 8 and 4, required for NDVI computation, are provided every 5 days). Using the Google Earth Engine platform, we retrieved already atmospherically corrected Sentinel 2 L-2 surface reflectance images from May 2017 onwards (March 2023). Only images with less than 40% cloud cover were selected. We computed the NDVI value for each image after masking clouds present in the scenes. After this, we computed monthly average NDVI images, which were then mosaicked to cover the MCM.

For each polygon resulting from the reclassification of LULC change, we computed an average monthly NDVI time series by calculating, over the area covered by the polygon, the average value of the monthly NDVI obtained from the processing of the Sentinel 2 images. At the end of the process, we obtained a monthly NDVI time series for each single polygon related to unchanged forest and afforested areas (i.e., related to classes FOR-FOR and IMP-FOR, UGA-FOR, ARA-FOR, PRM-FOR, PAS-FOR, SHR-FOR), containing an NDVI average value per each month from May 2017 to March 2023. It should be noted that non-forested areas with an unchanged LULC (i.e., classes IMP-IMP, UGA-UGA, ARA-ARA, PRM-PRM, PAS-PAS, SHR-SHR) were considered as a single polygon and therefore a single NDVI time series was generated for the whole unchanged area.

2.4 Statistical Analysis

A yearly NDVI shape was produced for each polygon by averaging NDVI values related to each month of the year (e.g., May-2017, May-2018, May-2022). Finally, a single yearly NDVI shape was computed for each category of LULC change defined in Table 1.

We assumed that there are differences in the NDVI average values in unchanged forest, recently afforested areas and unchanged LULC in the surrounding of afforested areas. To compare these three categories, we computed maximum, minimum and average NDVI values. On this basis, we performed the Wilcoxon test [29] to compare NDVI average values of unchanged forest and recently afforested areas assessing whether there are significant differences between the state of health of afforested areas and the one in unchanged forest as reference state.

3 Results

3.1 Land Use/Land Cover Change Classification

The reclassification identified 4,337 ha of unchanged forest (about 3% of MCM). Considering the LULC change, a total of 1,142 ha was converted from impervious soil, artificial, non-agricultural vegetated areas (i.e., urban green areas), arable lands, permanent crops, pastures and shrublands and open spaces with little or no vegetation, to forest. The conversion from arable lands to forest (ARA-FOR) is the class with the highest extent area that have been transformed, followed by the conversion of shrublands and open spaces with little or no vegetation (SHR-FOR), pastures (PAS-FOR), artificial, non-agricultural vegetated areas (UGA-FOR), permanent crops (PRM-FOR), impervious soil (IMP-FOR) to forest (see Table 2). The arable lands, pastures and permanent crops classes make the 57% of the total of recently afforested area, implying that most of afforestation process in MCM occurs at the expense of agricultural areas. On the contrary, the conversion of impervious soil to forest makes about only 8% of the total of recently afforested area.

Figure 2 and Table 2 show the result of reclassification.

Table 2. The unchanged forest and different afforested areas (class), the related hectares (area (ha)), the count of polygons referred to each class (count) and the average polygon extent in ha (avg area) are reported. Refer to Table 1 for abbreviations of afforested areas.

Unchanged forest (1954–2018)			
class	**area (ha)**	**count**	**avg area**
FOR-FOR	4,337.75	1052	4.12
Afforested areas (2012–2018)			
class	**area (ha)**	**count**	**avg area**
IMP-FOR	88.93	200	0.44
UGA-FOR	111.47	105	1.06
ARA-FOR	367.03	726	0.51
PRM-FOR	96.86	95	1.02
PAS-FOR	190.47	407	0.47
SHR-FOR	287.64	303	0.95

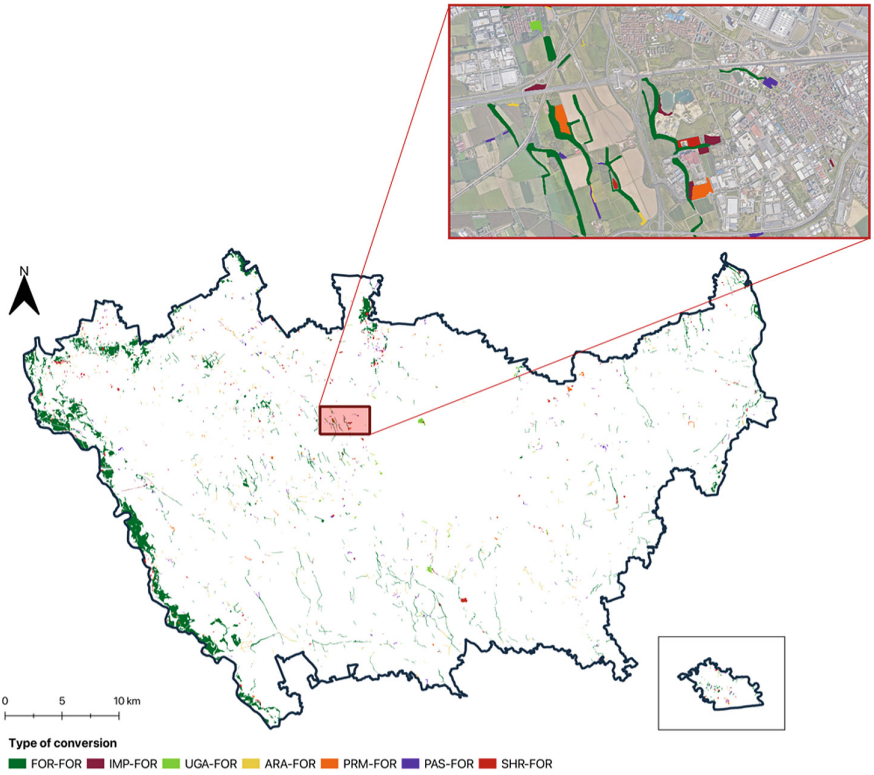

Fig. 2. Map of the unchanged forest (1954–2018) and LULC transformation due to recent afforestation process (2012–2018) occurred in MCM. Data elaborated from DUSAF (Destinazione d'Uso dei Suoli Agricoli e Forestali) database, ERSAF Lombardy region (https://www.geoportale.regione.lombardia.it/).

3.2 NDVI Values

As earlier mentioned, for each area identified through reclassification, the yearly mean values of NDVI have been computed. The main results are summarized in Table 3. In detail, the transformation of impervious soil to forest is the conversion class with the lowest mean NDVI values (mean value < 0.6). Instead, the conversion of pastures (PAS-FOR) and permanent crops (PRM-FOR) to forests are the classes with highest mean NDVI values (mean value 0.655 and 0.658, respectively).

According to the Wilcoxon test results, only 3 classes of afforested areas showed statistically significant difference ($p < 0.001$) with unchanged forest values, i.e., conversion of impervious soil (IMP-FOR), arable lands (ARA-FOR) and pastures (PAS-FOR) to forest.

Table 3. Per each unchanged forest and different afforested areas classes, the mean NDVI, the standard deviation (sd NDVI), the maximum and minimum values and the related range (max NDVI, min NDVI, range (max-min)) and the p-value are reported. Refer to Table 1 for abbreviations of afforested areas.

Unchanged forest (1954–2018)						
class	**mean NDVI**	**sd NDVI**	**max NDVI**	**min NDVI**	**range (max-min)**	**p-value (NDVI year)**
FOR-FOR	0.648	0.052	0.785	0.438	0.346	NA
Afforested areas (2012–2018)						
class	**mean NDVI**	**sd NDVI**	**max NDVI**	**min NDVI**	**range (max-min)**	**p-value (NDVI year)**
IMP-FOR	0.588	0.079	0.716	0.397	0.319	<0.001
UGA-FOR	0.626	0.072	0.765	0.427	0.338	0.0053
ARA-FOR	0.620	0.057	0.738	0.440	0.299	<0.001
PRM-FOR	0.658	0.050	0.806	0.456	0.351	0.0544
PAS-FOR	0.655	0.062	0.776	0.465	0.311	<0.001
SHR-FOR	0.649	0.064	0.799	0.430	0.369	0.1130

The analysis of NDVI in afforested areas, i.e., areas transformed from other LULC (2012) to forest (2018), shows that, on average, the cold and growing seasons are very similar in almost all the afforested areas from different LULC classes (i.e., IMP-FOR, UGA-FOR, ARA-FOR, PRM-FOR, PAS-FOR, SHR-FOR) compared to the NDVI trend of the unchanged forests (FOR-FOR). From March, corresponding to the beginning of the growing season, NDVI starts to increase reaching a peak in May for afforested areas from permanent crops, shrublands, pastures, urban green areas and impervious soil; instead, the time of maximum greenness of afforested areas from arable lands varied between June and August, as in the case of unchanged forests.

The highest average NDVI values (maximum greenness) are reached in afforested areas from permanent crops (0.658), slightly lower in pastures (0.655), shrublands (0.649) and unchanged forest (0.648). The afforested areas from the impervious soil class have the lowest NDVI value in every month and on average (0.588).

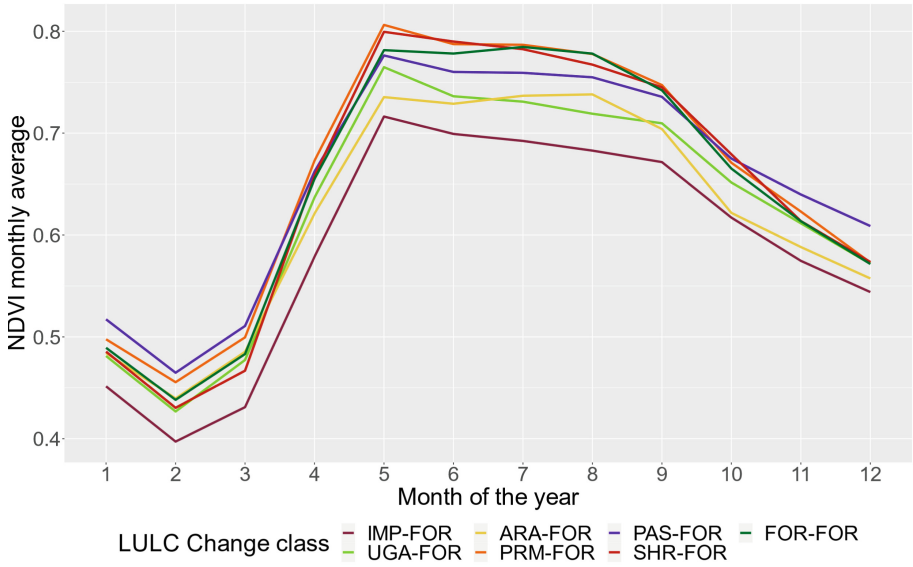

Fig. 3. Seasonality of NDVI values (average) in unchanged forest (FOR-FOR) and afforested areas from different LULC. Refer to Table 1 for abbreviations of afforested areas.

3.3 NDVI Comparison Between Afforested Areas and Unchanged LULC in the Surrounding

Table 4 and Fig. 4 show a comparison between areas that have been recently afforested with areas in their surrounding (within 1 km distance) which, in contrast to the afforested areas, maintained the same LULC in 2012 and 2018.

There are differences in NDVI increasing between afforested classes. The conversion from impervious soil to forest (IMP-FOR) reports the highest NDVI increment (0.29), followed by shrubland (SHR-FOR, 0.13) and then arable lands (ARA-FOR, 0.12) to forest. The lowest average increment is referred to the conversion of artificial, non-agricultural vegetated areas (UGA-FOR, 0.06), i.e., urban green areas, and permanent crops (PRM-FOR, 0.05) into forest; the gain is concentrated in months from May to September while for winter months values are similar. On the contrary, the conversion of pastures to forest (PAS-FOR) implies an NDVI decrease (−0.03). Considering the average maximum NDVI, the difference of IMP-FOR is even higher, reaching average value of 0.38. Instead, the difference in NDVI values between afforested areas and the unchanged LULC in surrounding of them are not relevant.

Table 4. Afforested areas from different types of LULC (rows) and related NDVI average and maximum values and the difference between the maximum and minimum NDVI values are reported (affor. columns) as well as NDVI average and maximum values of the unchanged LULC surrounding the afforested areas and the difference between the maximum and minimum NDVI value (ref. columns). The difference between afforested areas NDVI values and those related to unchanged LULC surrounding afforested areas are also included (delta columns).

	ref. LULC meanNDVI	**affor.meanNDVI**	**deltameanNDVI**	**ref. LULC max NDVI**	**affor.max NDVI**	**deltamax NDVI**	**ref. LULC rangeNDVI(max-min)**	**affor. RangeNDVI (max-min)**	**delta rangeNDVI (max-min)**
IMP-FOR	0.29	0.59	0.29	0.33	0.72	0.38	0.09	0.32	0.23
UGA-FOR	0.57	0.63	0.06	0.65	0.76	0.11	0.19	0.34	0.15
ARA-FOR	0.50	0.62	0.12	0.66	0.74	0.08	0.26	0.30	0.04
PRM-FOR	0.61	0.66	0.05	0.69	0.81	0.11	0.19	0.35	0.16
PAS-FOR	0.69	0.66	− 0.03	0.75	0.78	0.03	0.15	0.31	0.16
SHR-FOR	0.52	0.65	0.13	0.63	0.80	0.17	0.28	0.37	0.09

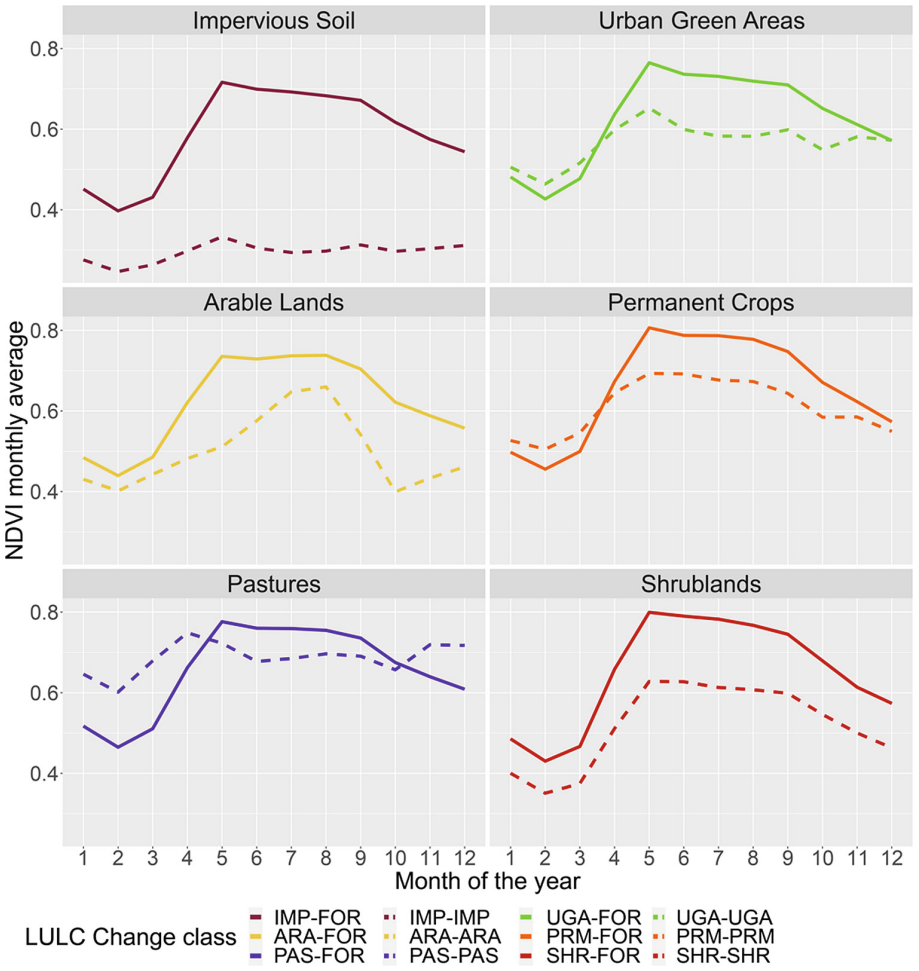

Fig. 4. NDVI trends in afforested areas originated from impervious soil (IMP-FOR), artificial, non-agricultural vegetated areas (UGA-FOR), arable lands (ARA-FOR), permanent crops (PRM-FOR), pastures (PAS-FOR) and shrublands (SHR-FOR) are reported (continuous line) in the same box with NDVI trends in the areas in the surroundings of afforested areas that have not changed LULC (dashed line). Refer to Table 1 for abbreviations of afforested areas.

4 Discussion and Conclusion

We tested our hypothesis to assess different vegetation states of health conditions in unchanged forest (1954–2018), recent afforested areas (transformed from other LULC (2012) to forest (2018)), and with unchanged LULC in the surroundings of afforested areas (2012–2018).

Although it could be reductive to compare two LULC solely on NDVI values, this study is the first attempt to analyze afforestation interventions, which should aim to have the same dynamics as natural ecosystems to be considered successful [14], and the

unchanged forests as the reference state. The Wilcoxon test results allow us to distinguish two groups of afforested areas (Table 3):

I) the group of afforested areas from different LULC with NDVI average values significantly different from that of unchanged forest;
II) the group of afforested areas from different LULC with NDVI average values similar to that of unchanged forests.

In detail, afforested areas from arable lands and impervious soil have statistically different mean NDVI values from unchanged forests. This is probably due to the intensive management of arable lands, which is correlated with low values of root length [30] and which, in turn, affects the vegetation growth [31]. Indeed, considering the effects on root length, LULC types are more important than site conditions [30]. The same can be applied to afforested areas from impervious soils. Instead, afforested areas from artificial non-agricultural vegetated areas, i.e., urban green areas, have similar NDVI values to unchanged forests, thus in line with studies in the literature [30] as well as permanent crops and shrublands.

Considering the average NDVI values change between the unchanged LULC classes in the surrounding of afforested areas and the recent afforested areas (Table 4, Fig. 4), the highest increase in NDVI values is related to the impervious soil to forest transformation mainly due to the greenness variation. The pastures, as unchanged LULC, present higher value in the cold season than afforested areas originated from them. The shrublands and afforested areas originated from shrublands maintain the same trend of NDVI average values in the year, as have a phenological behavior similar to the one of trees [32].

According to the results, particular attention should be paid to monitoring the afforestation intervention in impervious soil and arable lands, being the categories that differ most from unchanged forest considered the average values of NDVI.

4.1 Connection of LULC Transformations, Vegetation Health and Urban Planning

The article demonstrated the validity of this approach to heuristically define the characteristics of the afforestation process through threshold analysis. At the same time, this method can pave the way for further studies in other geographical and climatic contexts that can employ a similar process and verify abrupt changes in this index and check them by field survey. As the NDVI is a seasonal indicator which is affected by climate-driving factors [33] and the vegetation growth is related to diverse vegetation and climate characteristics [34], the exact definition of common threshold values used in different cases is not fixed. Even though other authors have already practiced this approach for different scopes [35, 36], we can confirm that NDVI trend analysis can be used for a relatively short-time monitoring aimed at verifying the human-induced changes in the landscape and supporting the decision-making for urban planning.

For example, as the NDVI has a positive correlation with vegetation biomass [37] and productivity [38] and different ecosystem services such as water yield, soil conservation, carbon storage and food supply [39], the results of the present study lay the basis for future planning scenarios aimed at increase ecosystem services. Thus, according to the main findings, in an afforestation scenario priority should be given to transforming

impervious soil and arable lands to forest with the main goal of increasing the greenness and vegetation health status of such areas. As highlighted by the research outcomes, reducing the anthropic footprint can be considered the most radical and tangible solution to potentially increase biodiversity, as land cover and NDVI are predictors of e.g. habitat selection along migration [40].

The NDVI variation between impervious soil to forested areas shows a gain which doubles the second highest transition typology: from shrublands to forest. This empirical evaluation has a strong policy implication since it confirms that urban greening policies aimed at changing impermeable to permeable surfaces can maximize many ecological benefits, e.g., restoring the biological quality and fertility of soil [41]. New permeable areas should replace the existing sealed areas to improve biodiversity performance and create ecological continuity among the main core natural areas internal and external to the urban fringe while fostering ecological connectivity and slow mobility. Detailed interventions can enhance de-sealing processes to improve water infiltration, reduce run-off, and increase water retention [42] in new afforested areas. Permeable pavements can substitute traditional asphalt with pervious concrete or interlocking and plastic grid pavers. These solutions are particularly effective in reducing surface run-off while augmenting evapotranspiration [43]. Besides, over the infiltration process, semi-permeable material allows higher evapotranspiration while filtering and storing rainwater [44].

Also, abrupt changes in the mean NDVI are observed in the transition from arable lands to forest. This specific transition is highly favorable for reducing climate change effects induced by intensive land exploitation due to agricultural production. Even though there is a huge trade-off between crop production and biodiversity [45], the re-naturalization of former agricultural land into forest can highly augment the nutrient retention in the soil particularly in the 10-year-old afforestation compared to 60–70 years-old-ones [46] augmenting carbon sequestration and biodiversity consequently. However, on the one hand, attention should be paid to improve soil conditions during the site preparation before tree and shrub plantings to support urban afforestation in increasing soil carbon concentrations, water holding capacity and nutrient retention, among others benefits [47]. This could limit the difference in average NDVI values between impervious soil and arable lands and shrublands (see Table 3). On the other hand, despite the considerable increase in the average NDVI value from arable lands to forest, it is worth considering that large scale afforestation occurs on arable or abandoned agricultural lands could have displacement effects elsewhere, such as deforestation, due to the import of agricultural crops and livestock [48].

Thus, it is crucial to plan in a targeted way, limiting the large-scale transformations, generally prioritizing the impervious soil transformation to forest and detailed afforestation interventions on other LULC considering the results of the present study and the inclusion of afforested areas in a broader urban and landscape planning aimed to restore ecosystems and enhance the related services.

4.2 Limitations

This study introduced a novel approach to monitor NDVI trends for specific LULC transformations. Specifically, yearly NDVI trends on afforested areas were compared to check whether it is possible to reach the same NDVI levels of unchanged forests. This

research question has been positively answered only for specific kinds of transitions, while not for others. However, the main limitations of this approach are: i) the lack of current and/or previous study on this subject that could be considered as an initial thresholds for an area subjected to naturalization process; ii) the reduced time-series of NDVI observation 2017–2023 that may not be sufficient to track the evolution of biodiversity increase during and after the afforestation process and, finally, iii) some intrinsic issue of NDVI data that make it a partial, seasonal and limited indicator whose employment is restricted to detect vegetation health status and not biodiversity assessment. We are aware that in this work we use NDVI as a proxy of vegetation performance which could be included in biodiversity modelling, however we cannot consider the empirical evaluation of NDVI as an assessment of biodiversity, since much more detailed, onsite-field analysis should be put in place to empirically check if and how much the afforestation process increased the ecological biodiversity in the catchment.

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Fragmentation Tool to Develop Ecological Network from the Local to the Municipal Scale

A Roadmap for Green Infrastructure Planning and Design

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Abstract. Nowadays, several experiences in the international literature show that a planning approach based on the ecosystem services (ES) paradigm can positively influence social dynamics and contribute to enhancing the quality of life in rural and urban environments. Despite this, in Italy, there is no mandatory-planning instrument that considers the green environmental issue as a priority component in planning and design land transformation. In this context, one possible way to introduce GI in spatial planning instruments consists in the design of the ecological network (EN) as a conceptual tool for nature conservation and sustainable land use planning. To do this, the article outlines a methodological framework to encourage the use of geo-mapping solutions for the spatial definition of the EN at both the territorial and municipal scales.

Results show the benefit of this methodology in the spatial recognition and characterization of territory open areas fundamental to design the connectivity of natural and semi-natural habitats to develop the GI at local and municipal scale.

Discussions highlight the importance of the tool to define new relationships between natural resources and agricultural landscape matrix that support high levels of biodiversity and guide green infrastructure planning.

Keywords: green infrastructure · ecosystem services · fragmentation analysis

1 Introduction

Several experiences in the international literature show that a planning approach based on the ecosystem services (ES) paradigm can positively influence social dynamics and contribute to enhancing the quality of life in rural and urban environments. In this sense, it is consolidated the concept that "in cities, land-use decisions made during the

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planning process determine the availability of ES fundamental to the wellbeing of urban population. Hence, the inclusion of ES in planning is essential to promote sustainable urban development" [1].

Despite the need to refers to new paradigms based on the provision of ES by green infrastructure (GI), [2] in Italy there is no mandatory-planning instrument that considers the green environmental issue as a priority component in planning and design land transformation. This is a consequence of the lack of a national framework law on land use that does not consider the role of GI and ES as fundamental in urban development [3].

In this context, one possible way to introduce GI in spatial planning instruments consist in the design of the ecological network (EN) as a conceptual tool for nature conservation and sustainable land use planning, generally developed by interdisciplinary group of sectoral experts from different specific fields (i.e. biology, agricultural, landscape architecture, planners).

Made by a series of 'environmental components' such as core areas, buffer zones, wildlife corridors, stepping-stones, and restoration areas, the EN forms the 'backbone' of the Urban Green Infrastructures (UGI) defined as 'a network of natural and seminatural areas with other environmental features that is supposed to deliver ecosystem services' [4].

In Italy, the concept of EN and then GI is legally recognized by the Italian law "Rules for the Development of Urban Green Spaces [5] that transposed the contents of COM/2013/249 "Green Infrastructure (GI) - Enhancing Europe's Natural Capital" [4] at the national level.

Here, the EN is considered as the basic instrument to plan and manage environmental issues and values in cities, able to preserve the floristic and faunistic biodiversity conservation at national scale [6].

Despite this, the transposition of these concepts into spatial planning instruments was entrusted by the various Regions and differentiated according to the various contexts which referred to the various sector plans with specific regional and regulatory frameworks. These critical aspects have determined an inconsistent framework of tools that hardly interact beyond regional boundaries.

Therefore, to define a working tool to support the management ecological networks beyond administrative fragmentation and across scales is needed.

Also, since the ecological network is made up of a set of many secondary networks [6] that need to be overlapped with land use at the city scale, this paper analyzes and taste a method to plan and design the environmental components that works across administrative boundaries, starting from the regional scale, to inter-municipal and municipal scale [7–9] that would be effective and replicable in different Italian and European context.

Therefore, with the aim of introducing the concepts of green infrastructure and ecosystem services within the Italian land-use plan, the article outlines a methodological framework to encourage the use of geo -mapping solutions for the spatial definition of the EN at both the territorial and municipal scales.

For this purpose, we describe an experimental study conducted in the municipality of Falconara Marittima (province of Ancona) located in Marche Region, in the central part of Italy, where we tested the tool Fragmentation developed in 'Landsupport' platform, a web-based smart geoSpatial Decision Support System (S-DSS, www.landsupport.eu).

Framed in the field of geo-mapping application to monitoring "land take [10] the use of this tool can give a methodological contribution to a performance-based analysis approach in support urban planning, helping in quantified and qualified places by the development of specific environmental and landscape indicators to support the decision-making process.

Results shows the benefit of this methodology in the spatial recognition and characterization of territory open areas (Unità di Territorio Aperto - UTA) fundamental to design continuity and connectivity [11] of natural and semi-natural habitats to develop the GI [12] at the local scale (*Rete Ecologica Locale, REL*) and municipal scale (*Rete Ecologica Comunale, REC*).

The last session highlights the importance of the tool in defining potential relationships between green resources and natural elements of value within the agricultural landscape matrix that support high levels of biodiversity, diversifying strategies to implement GI in natural and rural landscapes and defining the rules for maintenance, valorization, or regeneration of natural capital.

2 Materials and Methods

2.1 Case Study

With the aim of supporting the public administration in drawing up the Green Plan [13] for the municipality of Falconara Marittima based on the definition of strategies to plan the green and blue infrastructure, we defined a cluster of five neighboring municipalities that has been considered strategical to design the ecological network at the local scale: a) Falconara Marittima, b) Montemarciano, c) Monte San Vito, d) Chiaravalle, e) Camerata Picena.

Their selection considers of the two main environmental system of (1) the north part of the coastal areas of Ancona, (2) the Esino river valley, made up by 4 ecological functional unit (Unità Ecologico Funzionali, UEF) of the ecological network of Marche Region REM (Rete Ecologica Marche, article n. 4, 5 [14]) n. 16, 76, 82, 21 (Fig. 1).

These units summarize the environmental system by integrating information of a vegetational, fauna and anthropic nature to characterize the ecological fabric in its different structural and functional articulations.

They are also considered the constitutive element of the REM, highlighting the interrelation between natural elements and anthropic activities that give rise to the diversity of typical landscapes of the Marche Region.

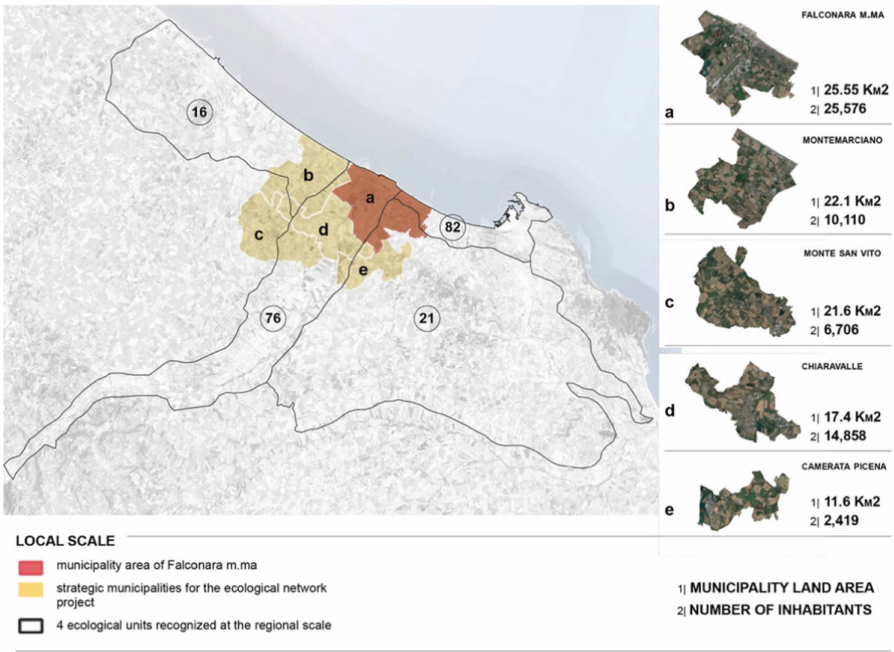

Fig. 1. Four UEF defined by REM, n. 16, 76, 82, 21. In red color: a) municipality of Falconara Marittima. In yellow color: localization of 4 neighboring municipalities interested by the downscaling process: b) Montemarciano, c) Monte San Vito, d) Chiaravalle, e) Camerata Picena.

2.2 Downscaling Method: Referencing from Regional to Municipal Scale

Starting from the selection of the environmental elements of values from the territorial and landscape tools, we grouped the spatial levels from the mandatory and non-mandatory planning instruments in 2 different levels, referring to ES literature [15]:

a) level 1 concerns all natural and ecological resources and mainly contributes to the spatial definition of the EN and so the GI; b) level 2 concerns historical and cultural elements and resources that could add value to the GI and give a specific characterization to a part of it.

At this point, to build the EN at the local scale we just considered the selected spatial levels from level 1, where the downscaling process of the ecological elements [16] have been taken from REM and transposed at the local scale of the ecological networks.

Differently, the downscaling of landscape resources to the municipal scale involved the spatial levels selected in level 1 and level 2 recognized in category (c) of the regional landscape plan (Piano Paesistico Ambientale Regionale – PPAR), and Provincial Territorial Plan (Piano Territoriale di Coordinamento- PTC) which could be physically connected to the primary ecological network (Fig. 2).

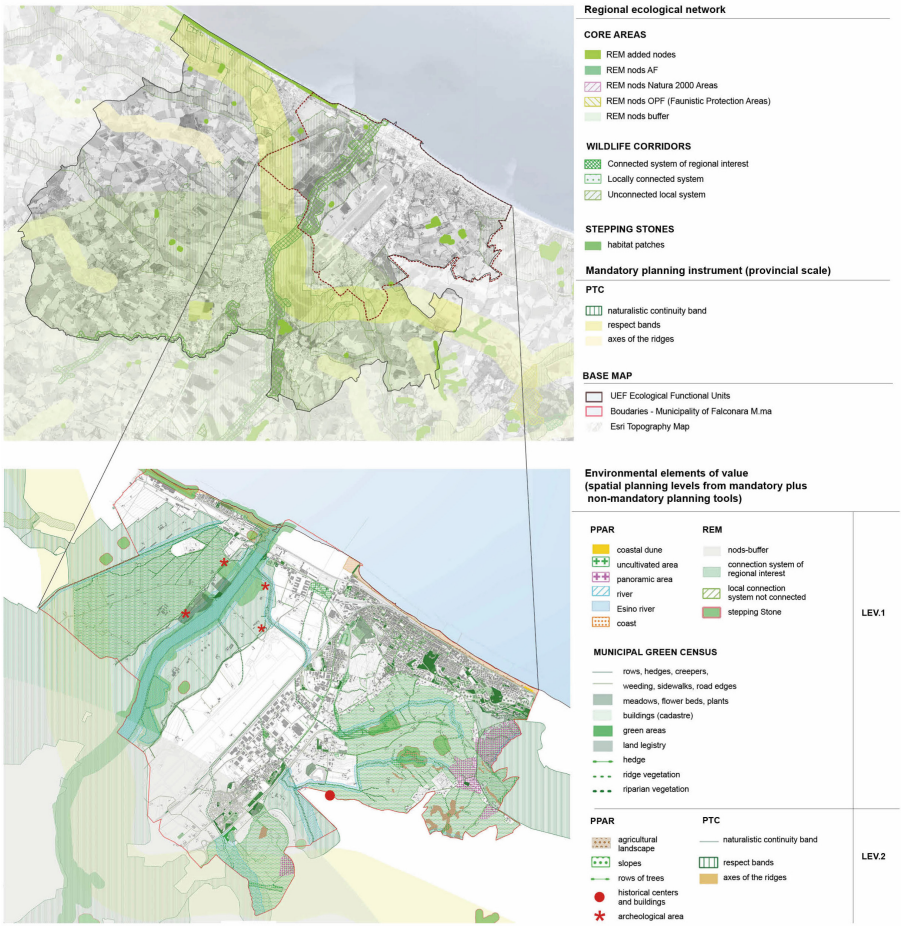

Fig. 2. Downscaling maps of the environmental elements from the territorial and landscape planning tools: local scale (top) and municipal scale (down).

2.3 Geo-Mapping to Help in the Decision-Making Process: The Tool 'Fragmentation' in Landsupport

Using 'fragmentation' tool (k3) from the Landsupport platform (Ka family of web-based geospatial knowledge - smart geoSpatial Decision Support System - S-DSS [17, 18]) we analyzed the continuity of natural areas by exploring a circle between 1 and 1,500 m with a fixed radius set for the five municipalities (defined spatial area – region - in a specific time).

Thanks to this application, we explored the degree of urban and rural fragmentation through an elaboration of an immediate picture of the areas affected by serious degradation processes of the rural territory.

Spatial analysis is based CORINE Land Cover CLC database [19] from EU Copernicus land monitoring services, developed to monitor of land take, land use and transformation, and their interaction within ecosystem services. Data start from year 2006 to 2020 and would be updated to the year 2023. For this case study, we selected images updated to 2020.

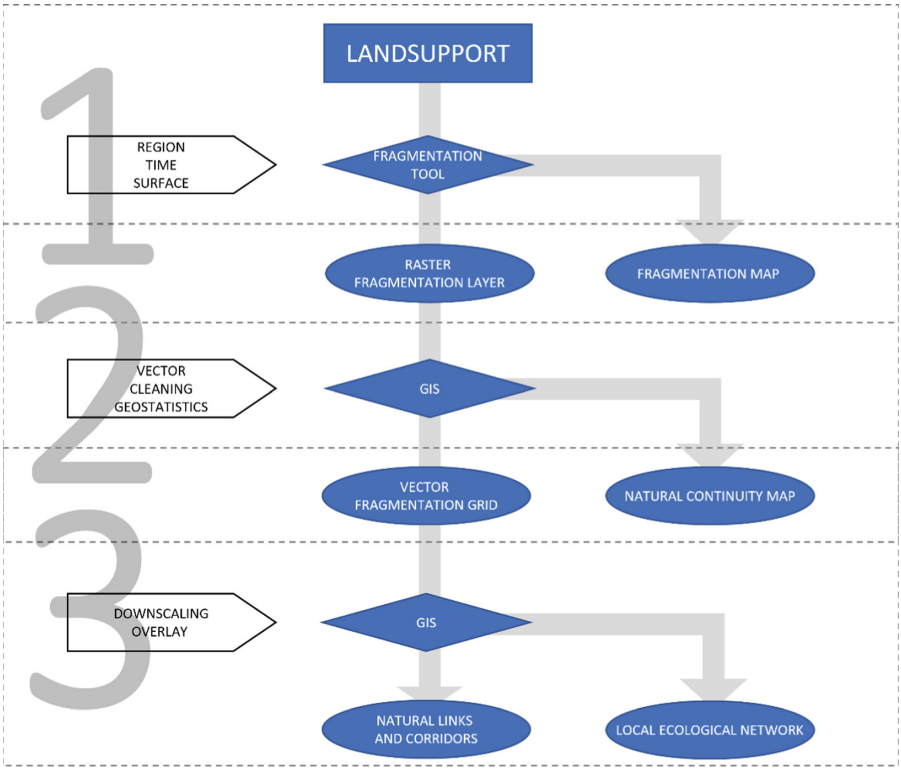

Fig. 3. Diagram of the research methodology based on multiphase and multiscale analysis.

Here, we adopted a multiphase and multiscale analysis based on the following three steps (Fig. 3):

Step 1 - raster fragmentation layer, consist in the downloading a geo-raster file (year 2020) from the application for all municipalities land area. Raster is set by a grid of 10 m * 10 m pixels with values between 0 and 1 to output the fragmentation level of the rural and natural areas, i.e. continuity of the open landscape areas. The value 0 indicates the maximum continuity of the regular grid model (or fishnet) while the value 1 indicates the maximum level of fragmentation (Fig. 4).

Step 2 - vector fragmentation grid, processed in GIS environment. At this step, we converted the raster file in a vector file to overlay the land-use map and selected all the records corresponding to urban areas or roads. By contrast, the values of continuity that

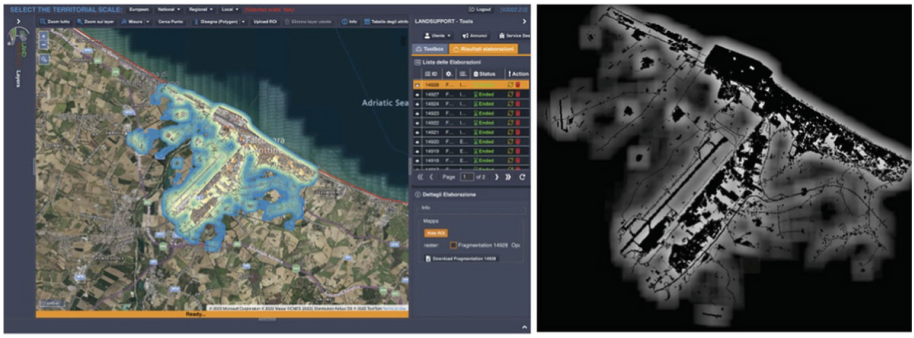

Fig. 4. Geo-raster file of fragmentation downloaded from Landsupport platform (www.landsupport.eu); on the left the graphical interface of the platform on the right an output raster image generate.

fall within these areas have been distinguished from the rural and natural areas of the municipal territory.

So, through specific analysis queries we filtered two different types of classifications functional to divide the urban areas from the natural areas.

Step 3 - geo-mapping the existing barriers and connections of the open landscape areas. At these level, environmental elements that comes from the downscaling process of territorial and landscape planning tools (described in paragraph 2.2) have been overlayed, to identify the potential relationship between the different levels of knowledge investigated with different planning tools at different scales.

3 Results

Starting from phase 1, the first result of the Landsupport implementation is the spatial definition of the levels of 'fragmentation' of natural habitat, identified at the local scale (inter-municipality system) and municipal scale (Fig. 5).

These maps represent the different levels of fragmentation in rural environment for the local and municipal scale, defining a gradient of the continuity index of the rural landscape. Here, the value of the index continuity of the peri-urban areas nearest to the urban areas tends from 1 (maximum level of 'disturb' of ecosystem dynamics) to 0 (highest level of continuity).

Comparing the two different scales of the case study, the range of fragmentation values decreased from 0.16 at the local scale to 0.098 at the inter municipal scale.

Therefore, on a municipal scale it is possible to consider areas with a value lower than 0.06 as continuous, while on an inter-municipal scale the threshold value is 0.03.

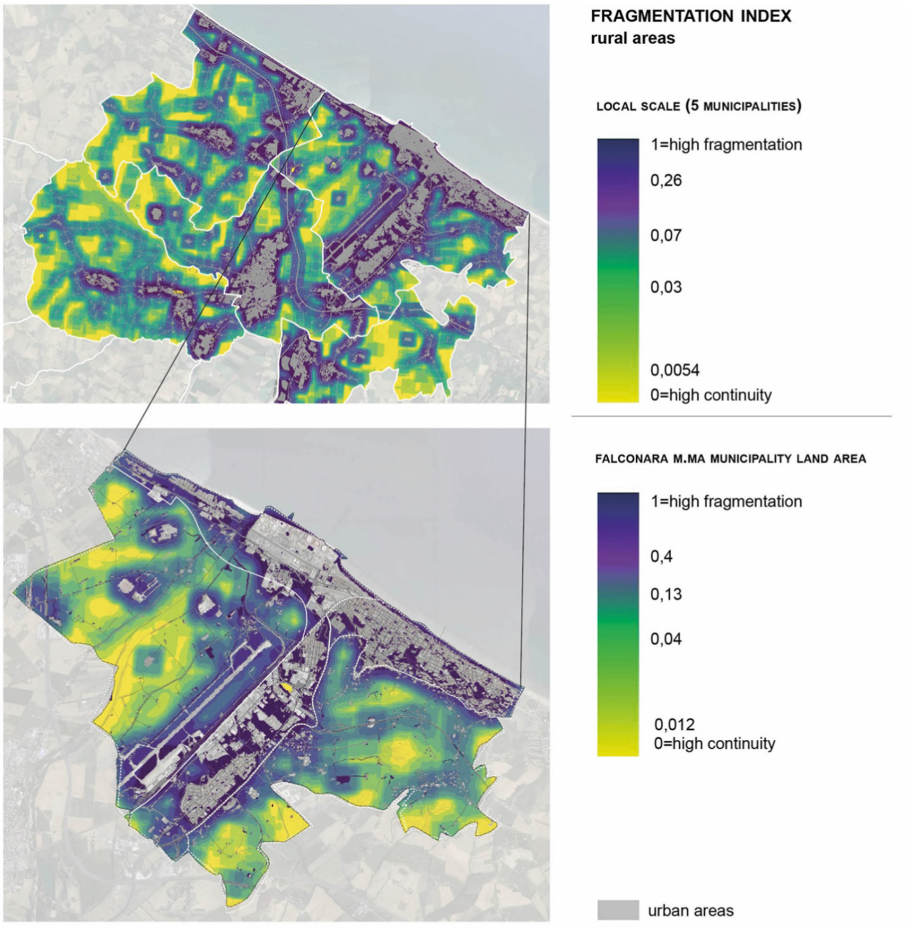

Fig. 5. Fragmentation map for the local scale (top) and municipal scale of Falconara Marittima (down) set in Landsupport platform (year 2023).

The second result consists in the definition of a vector grid processed in GIS environment to characterize rural landscape by applying geostatistical analysis to quantify and describe different areas. Specifically, for the municipality of Falconara Marittima we evaluated: a) average index of fragmentation of extra-urban natural areas; b) the total surface of rural areas with levels of continuity higher than the average fragmentation index; c) the ratio between the level of fragmentation of the rural and the urban areas on the total municipal areas; d) the ratio between the level of fragmentation of the rural and the urban area on the total of rural areas of the municipality (Table 1). These data are essential to quantify the urbanized area at the municipal scale, and to monitor dynamics of soil consumption.

Furthermore, starting from the evaluation of the levels of fragmentation we defined the territory open areas (Unità di Territorio Aperto – UTA) with a high level of connections, as essential components of the ecological network to be interconnected (Fig. 6).

Table 1. Characterization of the rural and natural landscape

Municipality land area (km^2)	Urbanized area (km^2)	Rural + natural landscape (km^2)	Urbanized area (% on the municipal land area)	Rural + natural landscape (% on the municipal land area)	F index*(Mean value)	Territory open area (UTA)**(km^2)	Territory open area (UTA)** (% on rural + natural landscape)
26	6	20	23	77	0,168	13	65

*F index = fragmentation index

**open areas characterized by a low level of fragmentation, that means a high level of continuity

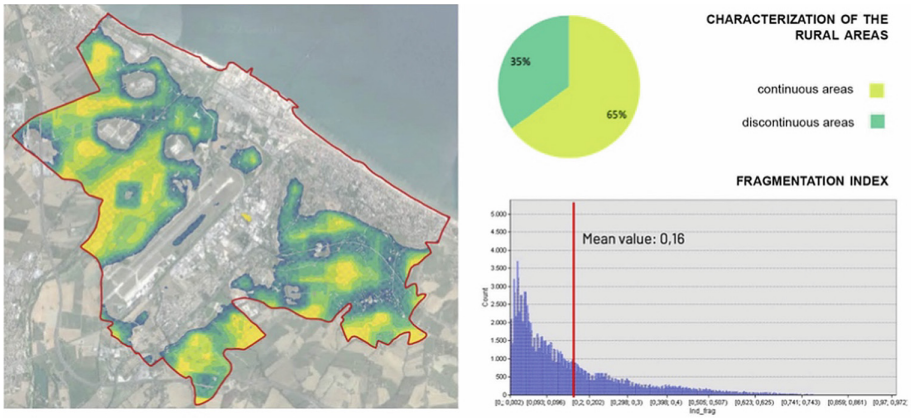

Fig. 6. Spatial definition of territory open areas (UTA) and characterization of the rural area of case study (municipality of Falconara Marittima, Marche Region)

The third result consists in the design of ecological network system at the local and municipal level, obtained from the spatial analysis deriving from Landsupport overlayed to the downscaling elements coming from the different current spatial planning tools.

At the local scale, the matching between spatial levels that comes from the traditional downscaling method and the open territory areas (Unità di Territorio Aperto, UTA, Fig. 7) allows to define the spatial development of local ecological network systems for the five-neighboring municipalities.

Here, the critical elements of the ecological network to preserve as a) core; b) buffer zones; c) ecological corridors, have been reconnected to the environmental matrix of agricultural areas that would support higher levels of biodiversity [20] and more environmental quality.

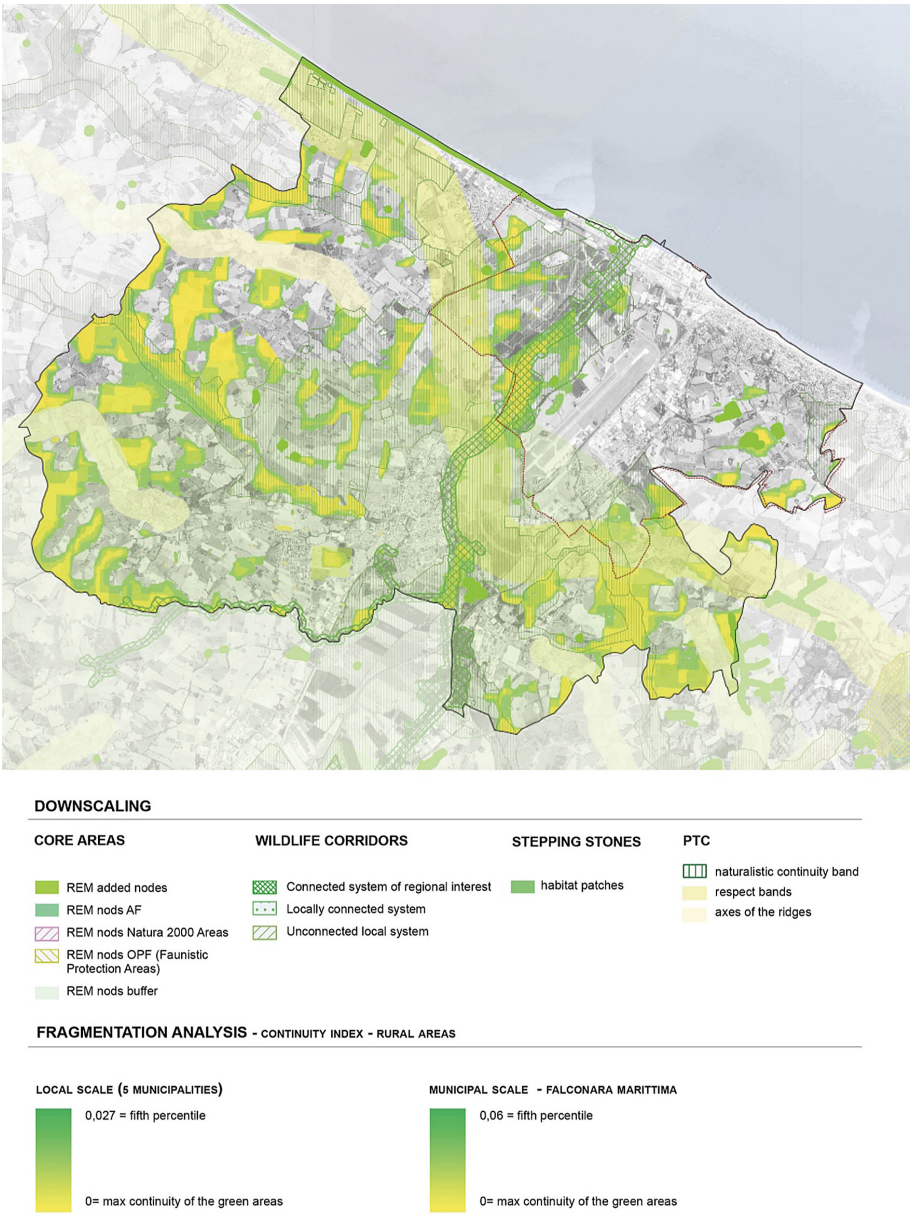

Fig. 7. Definition of the ecological network (REL) for the five municipalities local system. Overlaying of the main component of ecological network at regional scale (downscaling) and the territory open areas (UTA) derived by the fragmentation spatial analysis.

At the municipal scale, this method allows us to: (a) plan the green corridors, (b) improve the potential connections between the existing natural resources and the agricultural areas, c) rebuild the continuity of ecosystems.

Identified as the main components of the ecological network, the use of financial resources on these elements would be necessary for the strengthen multifunctionality and therefore the supply of ES to the city.

At this stage, the spatial level of the primary network systems of green spaces, GI, of the municipal scale (Fig. 8) supported in the definition and develop of strategical actions supported by the employment of nature-based solution (NBS): a) to recognize existing barriers to rebuild the continuity of ecosystems; b) to preserve/reinforce existing connection to strengthen the ecological system; c) to design new connections to achieve ecological connectivity (Table 2).

Table 2. Design lines to implement the ecological network at the local scale.

Elements	Description	Planning design and actions (Existing/Prevision)	
		Existing	Prevision
Barriers	Infrastructure or urbanized areas which block the transition of animal and plant populations	Provide defrag actions (by adopting nature-based solutions i.e. wildlife bridges, underpasses etc.)	Provide mitigation action to avoid fragmentation dynamics (by adopting nature-based solutions i.e. wildlife bridges, underpasses etc.)
Connections	Existing natural elements in non-urbanized areas		Provide design action – NBS solutions starting from the framework of the Ecological Network
	Natural elements in big parks reserve, Natura 2000 site, ecc	Planning intervention to preserve/strengthen the existing natural capital	

Since the fragmentation analysis contributes to the definition of strategic planning actions for GI development at the municipal scale (Fig. 8), we define the multiple ecosystem services provided by the GI planning action (already defined by the downscaling method plus multiphase fragmentation analysis), developed following the cascade model [15] (Table 3).

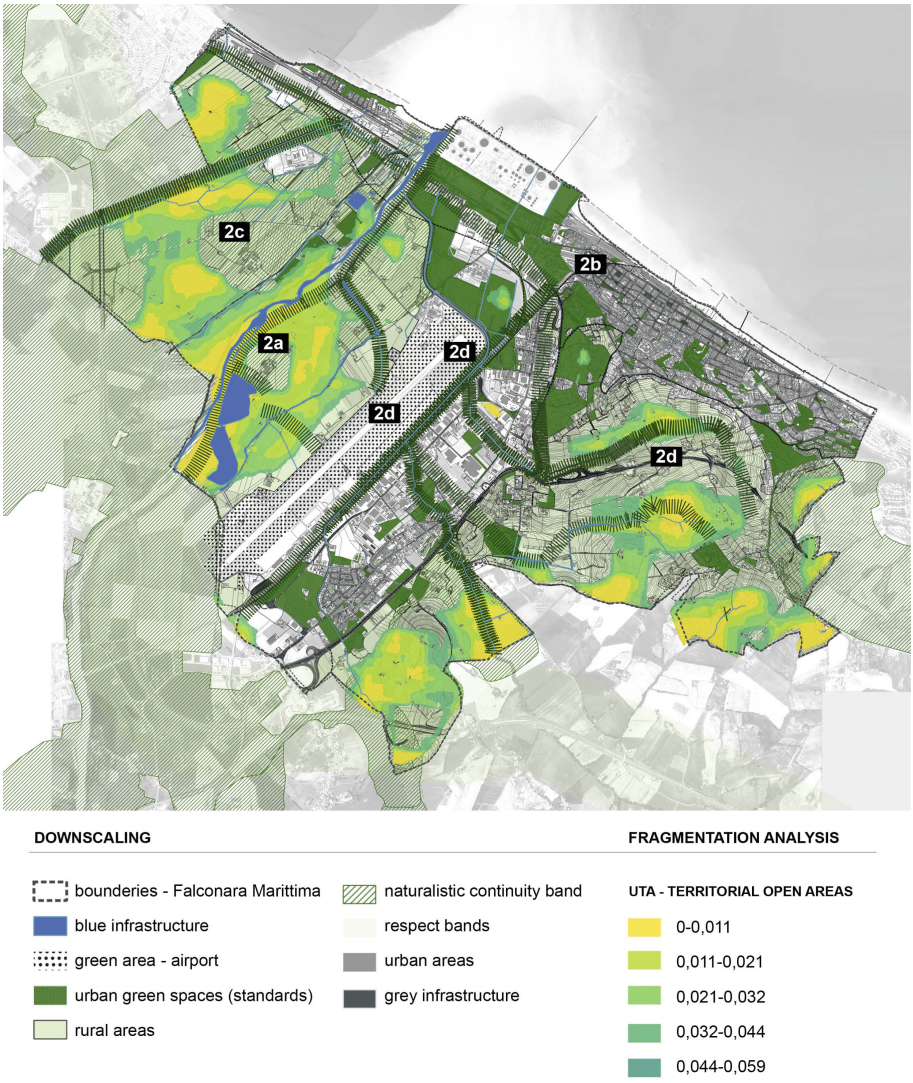

Fig. 8. Definition of the ecological network (REC) for the municipality land area. Overlaying of the main component of ecological network at regional scale (downscaling) and the territory open areas (UTA) derived by the fragmentation spatial analysis.

Table 3. Relationship between GI design action and ES potentially provided by theme [21]

Project area	GI design action (n.)	GI design action (description)	Management strategies	Type of action*			ES provided (prevalent)
				Ma	Va	Re	
Water bodies	**2a**	Strengthening of the role of the blue network of channel and ditches of the Esino river inside the Ecological functional Units identified by the REM	Encourage regeneration of shrub and herbaceous species (spontaneous or planted) [22]			x	Water regulation - Erosion control and sediment retention
			Encourage the planting of mesophiles and hygrophilous species along the riparian strips, also by providing for short rotation plants to produce woody biomass [22]		x		
			Avoid tillage in the buffer zone 4 m from the embankment	x			
			Renaturalization of the banks of lakes and ponds			x	
Woods	**2b**	Upgrading of existing forestry system	Conservation of wooded areas and re-naturalization with native species to enhance floristic richness and stability of the system		x		Pollination and biological control
			Provide shrubby vegetation strip at the edge of cultivated areas		x		

(*continued*)

Table 3. (*continued*)

Project area	GI design action (n.)	GI design action (description)	Management strategies	Type of action*			ES provided (prevalent)
				Ma	Va	Re	
Agro-ecosystems	**2c** **2d**	Strengthening of the ecological network within agricultural peri-urban areas (farm roads, canals and ditches, field border system)	Promote agriculture with a low environmental impact, reducing the use of pesticides and fertilizers	x			Landscape perception (traditional/ cultural value)
			Conserve and restore the traditional elements of the rural landscape in arable areas, such as isolated tree elements, rows, hedges	x			
			Maintain buffer strips at the margins of arable land with the use of mixed native species	x			
			Provide shrubby vegetation strip at the edge of cultivated areas		x		
		Reconstruction of the network of green corridors and natural elements through cultivated areas	Encourage sustainable mobility systems within cultivated areas		x		Recreational

(*continued*)

Table 3. (*continued*)

Project area	GI design action (n.)	GI design action (description)	Management strategies	Type of action*			ES provided (prevalent)
				Ma	Va	Re	
Urban settlement and infrastructure	**2e**	Design and management of urban green spaces to promote the conservation of biodiversity and soil protection	Provide for environmental compensations for new interventions		x		Climate regulation (air cooling) Gas regulation Soil permeability
			Strengthen the environmental compensations in productive areas		x		
			Reinforce the public and private green spaces in urban areas (zone C - expansion areas)		x		
			Promote the ecological permeability of the soils in project areas	x			
			Encourage the permanence of birds in urban and peri-urban areas	x			Refugia
			Protection of the row of trees and replanting where necessary	x			Disturbance regulation
			Mitigation of infrastructures by planting wooded strips			x	

* Ma = Maintenance; Va = Valorization; Re = Regeneration

4 Discussions

The territorial analysis of fragmentation levels in Landsupport platform is a useful tool for public administrations in facilitate the decision-making process on spatial planning namely to take decision avoiding new land take and enhancing natural assets in urban planning.

In fact, to guarantee the achievement of new quality standards imposed at the regional, provincial, and metropolitan levels of planning in sustainable urban development, it supports both technical and political parts involved in the land use planning and management of natural resources.

Today, the contents and range of territorial plans do not only consist of common updates but require a radical improvement in the potential and conception of the instrument itself to stop dispersion and facilitate compact urban areas. Indeed, spatial, and ecological fragmentation constitutes one of the principal causes of degradation at a regional level, meaning that it will be necessary to aim for defragmentation through numerous initiatives on different scales.

In this perspective, fragmentation map helps to a) increase specific knowledge in dynamics of urban development; b) evaluate the state-of-the-art analysis based on specific indicators to foresee the potential consequences of the various actions to be planned.

In future perspective, a possible implementation of these study consists in the evaluation of the level of proximity of the UTA as restoration areas to the urban green spaces (i.e. urban parks and gardens) In fact, to verify the accessibility but also the availability of the UTA from the rural to the urban areas is necessary to evaluate the provisioning of ecosystem services in relation to demographic dynamics and social *milieu* of the cities inhabitants.

With reference to the case study, the multiphase analysis provides different outputs with different purposes:

Firstly, the spatial definition of land use and land consumption dynamics during the time allows to provide the degree of fragmented areas (compromise area) on a municipal scale showing an historical trend of this dynamics.

Also, the evaluate the discontinuity of ecological connections is fundamental to understand the processes of degradation of ecosystem functions, which are the main cause of land use degradation.

Therefore, considering that the GI is a concrete action to mitigate the effects of soil sealing, [23] fragmentation map would be opportune in supporting the definition of the zones in which establishing protected natural areas of local interest and so in the implementation of strategies to reduce soil consumption, to protect and to preserve soils degradation. In fact, soil consumption and soil degradation are the main cause of the loss of ecosystem services as water regulation and air quality, where the growth of human activities and the sealing process (which causes fine particles and air pollution) counts around 4.2 million deaths every year in Europe [24].

Also, the vectorization of the ‘negative’ of the spatial analysis of the fragmentation defines the UTAs seen as ‘restoration areas’ within the landscape matrix, fundamental for reconstructing the ecological corridors from rural to natural spaces.

About the limitations of this study, we highlight some critical issues related to the implementation of the tool fragmentation:

Firstly, since the analysis is based on the photointerpretation of spatial surface types, in some cases different surfaces with similar colors are still interpreted as analogous.

Secondly, the raster output from the Landsupport platform represents both urban and peri-urban areas with the same values of continuity.

In fact, since the tool analyzes the continuity of the areas, a rural area assumes the same level of continuity as an urban area. Therefore, further refinement of spatial data is required.

This means that it is necessary to carry out geoprocessing operations to separate the urban from the peri-urban areas and to isolate the portions of natural territory characterized by a high level of continuity from the urban ones.

Although these operations are carried out semi-automatically using layers from regional databases such as, for example, the Atlas on Soil Sealing [25] it needs to be corrected with a manual implementation that can be time consuming and requires specific knowledge of the different context. Furthermore, this type of operation is feasible on a municipal scale but much more difficult for wider contexts.

Lastly, the implementation of GI design action supposes a critical selection of the ecological connection to invest in NBS with priority over the others.

This asset required knowledge of the locations (project areas) and integration with the site investigations and specific agronomic and botanic-vegetational studies to support the analysis of local data.

5 Conclusions

Since the inclusion of ES in planning is essential to promote sustainable urban development, a new planning approach that considers the integration of GI as the spatial design tool to deliver ES in urban and peri-urban areas is now required.

The contribution illustrates a potential method for integrating GI within the common European and Italian planning practices. It describes a multi-scale and level approach based on ecological network integration for GI development, starting from the local scale to define the strategic action at the municipal scale to update the current urban plans in force.

Focusing on the analysis of 'fragmentation' using the 'Landsupport' platform to support and facilitate the decision-making process, the case study demonstrates that the use of new planning tools to easily achieve and process specific data and knowledge in the dynamics both urban and environmental development can positively contribute to developing GI strategies within traditional planning tools.

To this end, it could represent a valid method to raise the awareness of the public administration, decision makers and technicians to introduce the concepts of green infrastructure and ecosystem services in spatial planning and properly manage these elements within the mandatory planning tool.

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Preventing Urban Floods by Optimized Modeling: A Comparative Evaluation of Alternatives in Izmir (Türkiye)

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Abstract. It is widely acknowledged that coastal cities will be heavily threatened by climate change globally. Among these cities, the Mediterranean suffers from a coupled dynamic of sea level rise and pluvial flooding due to their landform and soil characteristics. In this situation, analyzing the morphological and hydrological characteristics to define vulnerable areas is a prerequisite to designing performance-based solutions. But how does the flood vulnerability change with the different configurations of pervious and impervious surfaces? How do soil and landform characteristics affect flood vulnerability? This study assumes the possibility of re-naturing the coastal neighborhood of Karsiyaka, Izmir (Türkiye) while using fifteen alternative scenarios. We modeled the Urban Flood Risk Mitigation using InVEST (Natural Capital Project) and integrated the results with an analysis of the flow accumulation. According to our results, when the de-sealing process occurs in soils with low hydraulic conductibility, the results in terms of run-off containment can be dramatically limited or non-perceptible. The findings demonstrate that modeling with scenarios can guide the decision-makers while understanding exactly where the de-permeabilization can achieve its maximum efficiency. Therefore, performance-based solutions designed to increase water infiltration should carefully consider ex-ante empirical modeling to prevent urban flooding.

Keywords: Urban Flood Management · Soil Permeability · Performance-Based Urban Planning · Ecosystem Services Modeling

1 Introduction

Global climate change has several effects on urban areas [1]. Changing climates also increase urban flood frequency and severity [2]. Pluvial floods occur when poor infiltration during cloudbursts prevents runoff management [3–5].

Urbanization, which increases the footprint of anthropic uses in the city and affects land use, makes stormwater management difficult and has many other detrimental

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impacts [6, 7]. Built-up regions diminish water penetration and increase runoff, making urban areas more susceptible to flooding [8–10]. Thus, the traditional planning approach, which prioritizes grey elements (roads, buildings, etc.) over green ones and arranges infrastructure elements like utilities and public facilities to create functional and livable communities [11], often falls behind in reducing runoff, especially in dense coastal cities where precipitation and storm events are common.

Deforestation, agricultural land destruction, and increasing impermeable areas for rapid city development to meet rising population and demand make flood disasters almost inevitable [12, 13]. To avoid flood damage, towns should be redesigned with natural environmental values. City natural features manage flood episodes via infiltration based on soil conditions and vegetation [14]. Planners must adapt to climate resilience as cities grow and climatic phenomena change quickly [15]. Ecosystem services and its components should be used to preserve city life for long-term adaptation [16].

As artificial land increases, biodiversity decreases, and natural areas are lost, integrating fast-developing cities with ecosystems to design performance-based natural solutions in urban spaces becomes more complex [17]. NBS measures evolve from the European Commission's ecosystem-based planning approach [18]. "Cost-effective solutions inspired and supported by nature, which simultaneously provide environmental, social, and economic benefits and help build resilience" are their description. "Locally adapted and systemic interventions bring diverse natural features and processes into cities," according to the European Commission [19]. These multifunctional processes help cities adapt to changing climates and benefit society [20, 21].

Due to conventional infrastructure's failure to manage the urban water cycle, interest in urban resilience has grown [22]. Long-term development is needed due to urban catastrophes' unexpected spread and climate change-induced severity [23]. Thus, cities must incorporate resilience into urban planning to improve disaster response [24]. NBS improve urban soil permeability, making "cloudburst resilient" cities possible. Cloudburst-resilient cities can swiftly recover from precipitation events and limit their negative consequences [3]. Densely vegetated, porous cities may absorb and retain more precipitation than sealed urban structures. By learning from past catastrophes, they may create and apply urban policies to mitigate future disasters [25].

In this manuscript, we tried to analyze the response of Izmir's land uses to flood risks through scenario development. The reason for the disasters experienced by the city was questioned in the following section. We then set fifteen different land use scenarios for the coastal neighborhood of Karsiyaka, Izmir (Turkey). While keeping in all scenarios the ratio between permeable and impermeable areas, we demonstrated how soil permeability and slope factor affect flood risk and runoff retention, thus influencing the final performance of NBS. We tested our results while modeling the Urban Flood Risk Mitigation with Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST). Though the model of InVEST is successful in measuring urban flood risk, it does not consider the slope factor. Since slope analyses alone cannot provide this data, we performed the FA analysis and integrated the results with InVEST model outputs.

Moreover, the flow accumulation (FA) process allows us to determine urban flood risk assessment, including the topographic condition of the area. Due to the slope factor, stormwater is unstable and always in constant motion [26]. In detail, the slope characteristic of an area plays a very important role in the fight against urban flooding [27]. Knowing the movement behavior of water during rainfall is critical in flood prevention efforts [28]. Integrating InVEST output and FA, we generated a flood vulnerability analysis that includes slope, soil structure and urbanization characteristics as input, directly affecting flood. We concluded the study by highlighting important policy implications and addressing possible studies that should be carried out in the future.

2 Materials and Methods

2.1 Area of Interest

Due to its semi-closed character, the Mediterranean Sea is changing quicker than the world average [38]. The Mediterranean is one of the most impacted areas in the world by the combined impacts of climate change, pollution, and urbanization [38]. Due to climate change and urbanization, Turkey may experience frequent and intense disasters like precipitation imbalances, temperature increases, and drought [39, 40].

Due to the intensive coastal population in Turkey's Western Aegean area, Izmir has a high sealed surface rate [41]. The province contains the study area, with a characteristic Mediterranean climate with warm, humid winters and scorching, dry summers. The province's annual average temperature is 18 °C, with winter temperatures of 9 °C and summer temperatures of 28 °C [42, 43].

Izmir has survived several tragedies over 500 years, developing a tenacious spirit that has helped it be a large city. Due to its dense structure and geography, the city has seen frequent floods, earthquakes, and fires [44]. Izmir's unsuitable and uneven urbanization is primarily overrun with agricultural lands, yet its natural and environmental qualities raise natural catastrophe risks [45]. This puts Konak, Karsiyaka, and Bayrakli at risk of flooding in Izmir [15].

With 4,425,789 residents [46], Izmir is Turkey's third most populous city. Due to that demand, the city's population has expanded by more than 50% between 1990 and 2018, and the urbanization process on sealed surfaces has surged to 99.3% and continues to increase [47]. This procedure has occurred throughout several floods. Floods at Karsiyaka and Cigli, Izmir, killed around 60 persons in 1995 [48]. In February 2021, the same cloudburst occurred. "Rainfall was 126 kg/m^2. 18% of rainfall is normally seen throughout the year," said Izmir mayor Tunç Soyer. This flood caused significant economic harm to the cities [49]. These instances demonstrate the need for an Izmir stormwater action plan or strategy [50].

This research sampled the Karsiyaka district as a case study (see Fig. 1). This sample was chosen because of its significant flood risk and urban transformation potential [15].



Fig. 1. Area of interest.

2.2 Urban Flood Risk Mitigation Model

The InVEST Urban Flood Risk Mitigation model is one of the most widely used tools to assess urban flood safety and risk areas [29–31]. The model simplifies infiltration using soil and land cover characteristics: locations with surfaces constructed on less porous soils (low drainage capacity) and large impermeable surfaces are at high flood risk. Thus, roads and industrial areas built on hydrologically impermeable soil have the highest risk of flooding [32]. The Runoff Curve Number (RCN) matrix calculates runoff using the parametric link between land use permeability and soil hydrological properties [33, 34]. RCN determines runoff from urban land use and soil hydrological conductivity.

An accurate biophysical estimation of urban runoff during a cloudburst can be difficult and complex [35] due to multiple variables affecting the discharge capacity of the area during a single rain event, such as building quality and quantity, infrastructure quality and capacity [36, 37]. InVEST model output indicates rain event runoff retention index and millimeters. InVEST's Urban Flood Risk Mitigation model requires five inputs: watershed vector data representing the area of interest, depth of rainfall for one cloudburst event in mm, a Land Use Land Cover (LULC) map representing the surfaces' impermeability ratio, a raster map of soil hydrologic conductibility, and biophysical values for each land use land cover class.

2.3 Land Use Land Cover Dataset

Table 1 shows the association between urban soil permeability and RCN categories (A, B, C, and D) in this study's land use categorization system. ArcMap sessions used

USDA classes and the Imperviousness High-Resolution Layer (HRL) database from the Copernicus Land Monitoring Service website (https://land.copernicus.eu/pan-european/high-resolution-layers/imperviousness, accessed 25.10.22) to classify land use. The HRL database shows the geographical distribution of artificially sealed regions and their sealing density [38]. Semi-automated categorization using calibrated Normalized Difference Vegetation Index (NDVI) readings determines the degree of sealed soil from 1–100% [39]. The dataset shows soil sealing rates and temporal change and defines sealed/impermeable places where the original natural/semi-natural land cover or water surface has been replaced with an artificial, typically impervious cover. These artificial surfaces need long-term maintenance.

In the research, the LULC map was constructed using two land use codes: green for permeable open places like urban parks and grey for artificial surfaces. The LULC setups utilized in the modeling situations will be explained.

Table 1. The relationship between the categories of land use and land cover and the runoff curve number. Source: United States Department of Agriculture (1986). Urban hydrology for small watersheds. Technical Release 55 (TR-55) (Second ed.). Natural Resources Conservation Service, Conservation Engineering Division.

Cover description		Curve numbers for hydrologic soil groups				LUCODE
		A	B	C	D	
Open space (lawns, parks, golf courses, cemeteries, etc.)	Fair condition (grass cover 50 to 75%)	49	69	79	84	Green
Residential districts by average lot size	$^1/_8$ acre or less (town houses) (65% imp.)	77	85	90	92	Grey

2.4 The Soil Hydraulic Conductibility

The second crucial input for the model is the map of saturated hydraulic conductivity (Ksat, mm/h, as shown in Table 2), which is defined as the soil's ability to be vertically crossed by fluids when saturated [40]. Hydraulic conductivity depends on soil porosity and, in turn, soil texture: clay soils generally have lower conductivity than sandy and gravel soils [41]. Soils with good porosity and conductivity allow for water retention and movement quickly. Water quickly reaches the aquifer with high conductivity, resulting in limited surface flow processes [42, 43]. In contrast, low infiltration in soils with poor conductivity generates high surface runoff rates [44].

For this study, an ancillary dataset was developed based on the more precise Geological Unit, utilizing raster reclassification. The classification process to assign a specific Hydrological Soil Classification, as proposed by Ross et al. (2018), is synthesized in Table 3. Additionally, the results of the classification are reported in the following Fig. 2.

Table 2. Parameters related to the ability of soil to transmit water. Source: InVEST User's Guide available at: https://invest-userguide.readthedocs.io/en/latest/urban_flood_mitigation.html

	Group A	Group B	Group C	Group D
Saturated hydraulic conductivity of the least transmissive (soil depth 50 and 100 cm)	>40 m/s	[40;10] m/s	[10;1] m/s	<1 m/s

Table 3. Table for conversion of Hydrological Soil Classification

Geological Units	Soil Groups	Geological Units	Soil Groups	Geological Units	Soil Groups
Clastic rocks	A	Pyroclastic units	D	Granitoid	D
Lime soil	A	Granitoid	D	Clastic units	B
Sediment soil	A	Oligocene volcanic units	C	Schist	D
Terrestrial clastic units	B	Volcano-sedimentary units	C	Gneissoid	D
Lacustrine limestone	D	Flysch	D	Meta-granitoid	D
Marn	D	Nautical limestone	B	Metamophic units	B
Shale	D	Ophiolite-serpentinite-basalt	D	Clastic units	B
Rhyolite	C	Marble	B	Carbonate units	B
Basalt	C	Limestone	B	Quartzite	D
Dacite	C	Neritic limestone	B	Quartzit-schist	D
Andesite	C	Carbonate	B	Phyllite	D

2.5 Flood Vulnerability Assessment

Landform-based FA shows water flow [46]. Pixel-based data predicts water pools. The slope factor influences water flow. A visual model of stormwater movements based on topography was created using 1:20,000 Copernicus Digital Elevation Model (DEM) data. FA maps are made in three steps. We adjusted base data pixel biases using Fill Sinks first. Since raster data may contain pixel-based inaccuracies, this phase is crucial for accurate analysis. Flow Direction estimated water flow directions during a cloudburst. Output analysis followed this. After these steps, the FA visual model was generated. Flood susceptibility was calculated by overlapping runoff and FA indexes. Theoretically, this stage indicates high-slope and stream areas where runoff may be more detrimental than expected.

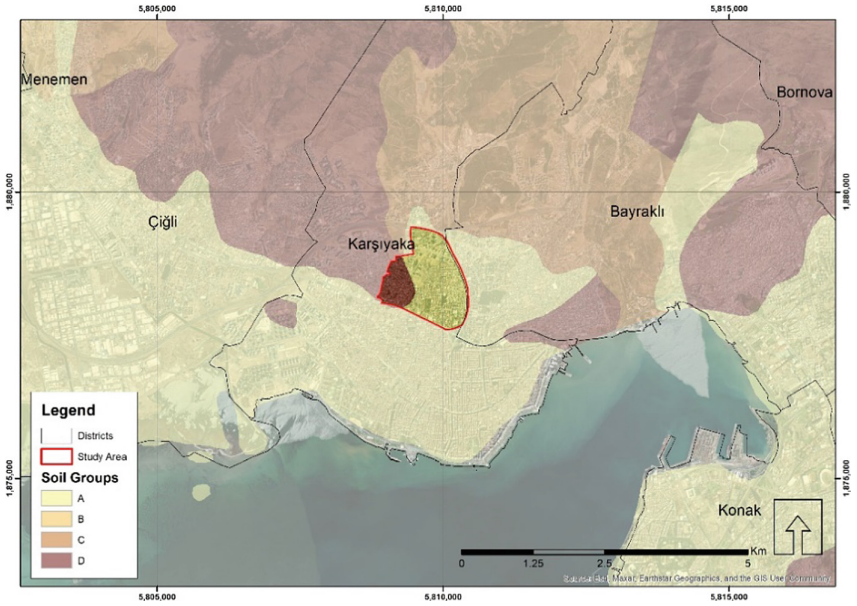

Fig. 2. Groups of soil types according to their hydraulic conductivity.

Karsiyaka's 70 mm cloudburst hazard zones may be recognized early using the composite index. It was selected because it met the "cloudburst" requirement but fell short of the November 2020 event's rainfall [29]. Turkey's Meteorological Agency (Meteoroloji Genel Müdürlüğü: MGM) recorded 42.1 mm of rain in Menderes and 77.3 mm in Karabağlar in November 2020, with other locations receiving 103.4 mm to 147 mm. The 70 mm depth and 200-year return length were rare, according to the IZSU water management evaluation [47]. In February 2021, MGM recorded 123.9 mm of rain in Konak and 130.9 mm in Menderes.

After building the visual model, FA and modeling findings were merged to perform the final Flood Vulnerability Index (FVI) of the area. ArcMap 10.8's Spatial Analyst Weighted Sum tool overlapped FA and InVEST values to construct the FVI.

It is crucial to note that because no threshold is provided in the urban flood vulnerability literature [48], the coefficients were deemed equal by accepting both inputs as equal. FVIs were created by normalizing and merging the two data sets. The index varied from 2 (InVEST output + FA (1)) to 0.

2.6 Scenario Settings

Fifteen LULC scenarios were created in the district using the Create Fishnet tool of ArcMap 10.8 to divide the area into equal 10 m tiles, classified as green (permeable) and grey (impermeable). The quantitative criteria used required green areas to cover 50% of the site, distributed in various ways to produce slightly different effects on flood risk (see Fig. 3). The scenarios are labeled based on the location of the green areas, with the first

eight scenarios following cardinal point and cartesian principles. The remaining scenarios are relatively homogeneous and designed by placing permeable areas vertically, horizontally, or intersecting each other. The last three scenarios, Horizontal Pinstripe, Vertical Pinstripe, and Tartan, are the most homogeneous and fragmented.

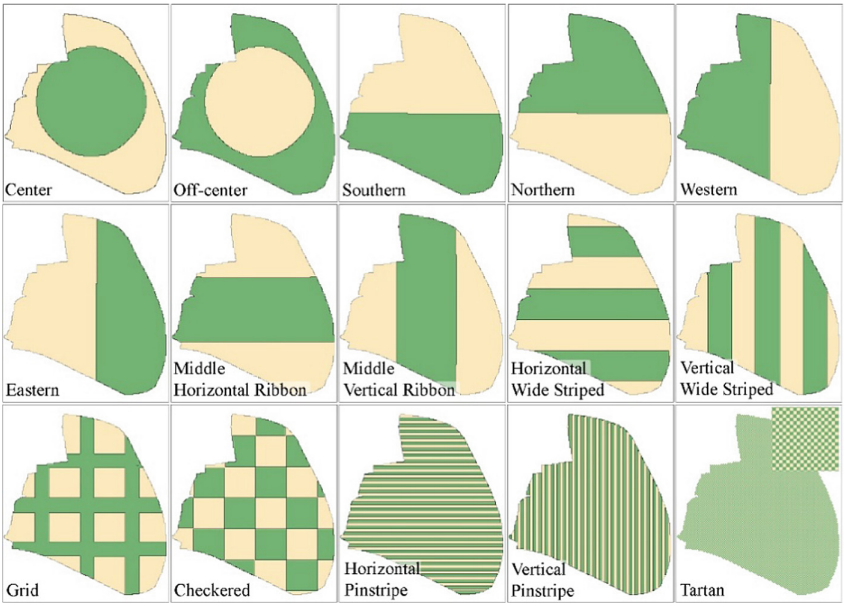

Fig. 3. Urban land use scenario designs produced within the scope of the study (green: permeable; beige: impermeable). (Color figure online)

3 Results

To measure the FVI, we used two indexes: runoff and FA. The results, presented in the Table 4, indicate a slight variation in the average values of runoff and FVI among the different scenarios.

The study's results revealed that the average runoff across all scenarios was 18.3 mm. The Western scenario had the highest runoff value of 18.954 mm, while the Eastern scenario had the lowest value of 17.593 mm. This indicates that the Western scenario had a higher runoff than the Eastern scenario. The difference in runoff between these two scenarios was 1.36mm, representing a 7.7% change.

Additionally, other scenarios had varying levels of runoff and FVI. For example, the Southern scenario had a runoff value of 18.386 mm and an FVI value of 0.376. The Northern scenario had a runoff value of 18.160 mm, and an FVI value of 0.368. The Center scenario had a runoff value of 18.177 mm and an FVI value of 0.370. These values demonstrate that while the Western and Eastern scenarios had the highest and lowest values, respectively, the other scenarios had values that fell in between.

It is also worth noting that even though the difference between the highest and lowest values in all the two cases (runoff and FVI) is not substantial. It indicates that the land use arrangements in the Western scenario make it more vulnerable to floods when compared to the Eastern scenario.

FA's influence on flooding risk (Table 5) shows that the two scenarios with the greatest risk (Western and Middle Horizontal Ribbon) and lowest risk (Eastern, Middle Vertical Ribbon) have not altered. The Northern, Center, Off-center, Checkered, and Southern situations remain in both rankings. This shows that FA little influences these scenarios' ranking changes between runoff and FVI.

In intermediate conditions, flood vulnerabilities shift. The Horizontal Wide Striped (runoff: 18.137 mm) scenario is the third least susceptible without topography, but with FA, it falls to seventh place with an FVI score of 0.370. When topography is included, the Vertical Wide Striped (runoff: 18.281 mm) scenario becomes the third least susceptible with an FVI score of 0.367. This scenario has improved the most among the fifteen scenarios in the calculation.

The Horizontal Pinstriped scenario upshifted two positions, making it less vulnerable to flooding, while the Vertical Pinstriped scenario downshifted two positions, making it more vulnerable, the Grid scenario upshifted one position, and the Tartan scenario downshifted three. Vulnerability has been utilized according to scenario rank.

It is fundamental to note that the flood vulnerability in the scenarios where the positioning of green areas are opposite can vary greatly, with one scenario being significantly high while the other being quite low (see Fig. 4). To explain, the Eastern and Western scenarios are obtained by designing permeable and impermeable areas in opposite positions. Similarly, in the Horizontal Wide Striped and Vertical Wide Strip scenarios, green areas are designed vertically in one and horizontally in the other.

4 Discussion

4.1 Investigation on Best Urban Settings Managing Flood Risk

In our analysis of the outputs generated by the InVEST model and the flood vulnerability maps, we discovered that the order of the maximum and minimum values of the scenarios did not undergo any alteration, implying that the influence of topography is not as significant as the hydrological conductivity of soil groups. In scenarios characterized by a low FVI, a frequent observation was the presence of densely concentrated green areas situated on soil with good porosity. If these green spaces are situated on soil with high permeability, the vulnerability of these scenarios to flooding is the least, and vice versa. This finding highlights the crucial role that soil types play in determining flood vulnerability compared to the area's topographic characteristics represented by FA.

Additionally, the urban scenarios developed within the scope of our work emphasize the pivotal role that land structure plays in preventing floods, in contrast to the influence of FA. Specifically, the difference between the Eastern scenario, which is the least vulnerable, and the Western scenario, which is the most vulnerable, can be attributed to the clustering of green and gray land uses in the east and west of the area, respectively. As can be inferred from the analysis, the Eastern scenario represents the optimal scenario for incorporating NBS into flood management plans.

Table 4. Measurement results of scenarios

Scenarios	Measurements	LUCODE	MEAN	SUM	Average
Center	Runoff (mm)	Grey	29.35	271,599.88	18.17766557
		Green	7.00	64,777.82	
	FVI	Grey	0.60	886.48	0.370379041
		Green	0.14	209.47	
Off-center	Runoff (mm)	Grey	27.79	257,091.14	18.36700177
		Green	8.95	82,790.23	
	FVI	Grey	0.57	836.91	0.374656687
		Green	0.18	271.70	
Southern	Runoff (mm)	Grey	27.65	255,806.88	18.38635431
		Green	9.13	84,432.60	
	FVI	Grey	0.56	834.49	0.376198328
		Green	0.19	278.68	
Northern	Runoff (mm)	Grey	29.49	272,930.14	18.16068613
		Green	6.82	63,133.36	
	FVI	Grey	0.60	888.90	0.3688374
		Green	0.14	202.49	
Western	Runoff (mm)	Grey	23.00	212,833.33	18.9548053
		Green	14.91	137,925.34	
	FVI	Grey	0.47	691.73	0.385708938
		Green	0.30	449.58	
Eastern	Runoff (mm)	Grey	34.14	315,926.68	17.59342168
		Green	1.04	9,639.58	
	FVI	Grey	0.70	1,031.66	0.35932679
		Green	0.02	31.59	
Middle Horizontal Ribbon	Runoff (mm)	Grey	25.15	232,690.72	18.69181125
		Green	12.24	113,201.25	
	FVI	Grey	0.51	746.48	0.378152859
		Green	0.25	372.47	
Middle Vertical Ribbon	Runoff (mm)	Grey	32.96	305,010.16	17.73618214
		Green	2.51	23,197.89	
	FVI	Grey	0.67	991.91	0.362423975

(*continued*)

Table 4. (*continued*)

Scenarios	Measurements	LUCODE	MEAN	SUM	Average
		Green	0.05	80.50	
Horizontal Wide Striped	Runoff (mm)	Grey	29.69	274,724.15	18.13787199
		Green	6.58	60,917.17	
	FVI	Grey	0.61	899.25	0.370647645
		Green	0.13	197.50	
Vertical Wide Striped	Runoff (mm)	Grey	28.49	263,655.46	18.28175123
		Green	8.07	74,648.34	
	FVI	Grey	0.58	834.14	0.367484817
		Green	0.17	253.25	
Grid	Runoff (mm)	Grey	28.10	260,082.04	18.33046095
		Green	8.55	79,123.14	
	FVI	Grey	0.57	836.19	0.370734129
		Green	0.17	260.82	
Checkered	Runoff (mm)	Grey	27.75	256,745.08	18.37395695
		Green	9.00	83,264.99	
	FVI	Grey	0.57	844.96	0.375710672
		Green	0.18	266.77	
Horizontal Pinstripe	Runoff (mm)	Grey	28.59	264,519.92	18.27096535
		Green	7.95	73,584.29	
	FVI	Grey	0.58	857.95	0.37064677
		Green	0.16	238.79	
Vertical Pinstripe	Runoff (mm)	Grey	28.59	264,554.63	18.27025189
		Green	7.95	73,536.38	
	FVI	Grey	0.59	860.04	0.370666329
		Green	0.16	236.77	
Tartan	Runoff (mm)	Grey	28.57	264,295.82	18.27081831
		Green	7.98	73,805.67	
	FVI	Grey	0.58	861.64	0.372051938
		Green	0.16	239.26	

To continue, the impermeable D-group soils are located west of the area, while the permeable A-group soils are east. Although the D-group soils occupy only a relatively small area, accounting for roughly one-third of the total area, their location in conjunction with green spaces increases the FVI of the area. In contrast to the study by Yang and Lee (2021), our findings demonstrate that by clustering green areas, on the soil types

Table 5. Comparative ranking of scenario results

Rank	Scenario	Avg. Runoff (mm)	Rank	Scenario	FVI
1	Eastern	17.59342168	1	Eastern	0.35932679
2	Middle Vertical Ribbon	17.73618214	2	Middle Vertical Ribbon	0.362423975
3	Horizontal Wide Striped	18.13787199	3	Vertical Wide Striped	0.367484817
4	Northern	18.16068613	4	Northern	0.3688374
5	Center	18.17766557	5	Center	0.370379041
6	Vertical Pinstriped	18.27025189	6	Horizontal Pinstriped	0.37064677
7	Tartan	18.27081831	7	Horizontal Wide Striped	0.370647645
8	Horizontal Pinstriped	18.27096535	8	Vertical Pinstriped	0.370666329
9	Vertical Wide Striped	18.28175123	9	Grid	0.370734129
10	Grid	18.33046095	10	Tartan	0.372051938
11	Off-center	18.36700177	11	Off-center	0.374656687
12	Checkered	18.37395695	12	Checkered	0.375710672
13	Southern	18.38635431	13	Southern	0.376198328
14	Middle Horizontal Ribbon	18.69181125	14	Middle Horizontal Ribbon	0.378152859
15	Western	18.9548053	15	Western	0.385708938

characterized by high hydrological conductivity and vice versa, a heterogeneous design can be established to create the least vulnerable urban district to floods.

The increasing built environment and soil loss with good hydraulic conductivity due to urban sprawl [50] make cities such as Izmir more susceptible to urban floods. Our results suggest that the strategic placement of green spaces can significantly reduce the risk of urban floods. These findings provide valuable insights into the relationship between land use configurations and runoff vulnerability and can aid in developing effective urban flood mitigation strategies.

4.2 Investigation on Effect of Flow Accumulation

The significance of FA in mitigating flood disasters has been widely acknowledged in the literature, as indicated by several studies [51–56]. Although the data did not significantly alter the ranking of the scenarios with varying levels of vulnerability, it did demonstrate a notable impact on the vulnerability index of certain areas in some scenarios (such as Tartan) in either a positive or negative direction. This underscores the fact that the FA is

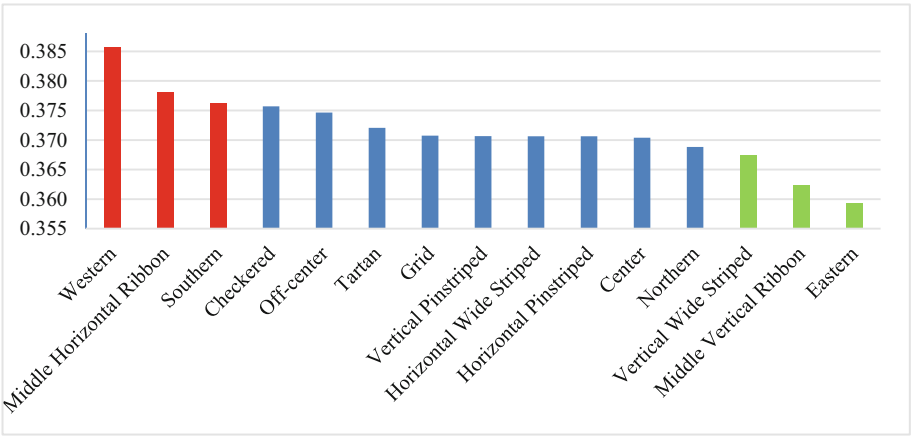

Fig. 4. Flood vulnerability indexes of the scenarios.

one of the most crucial factors to consider, after soil characteristics, in mitigating urban flood risk.

It is crucial to remember that integrating FA into urban planning and design is both a technical and policy challenge. Governments and regulatory bodies must create the necessary legal frameworks and standards to ensure the proportionality of soil and FA characteristics in urban planning and design processes. To assist this, a multidisciplinary approach involving the professions like urban planners, landscape architects, architects, geologists, and civil engineers is needed to effectively address urban flood risk and design sustainable urban drainage systems. Furthermore, the creation of legislation and policies is critical in the development of integrated and sustainable urban drainage systems that are based on NBS. Such systems prioritize the use of natural elements such as vegetated roofs, green walls, rain gardens, and permeable pavements to reduce runoff and enhance water infiltration. Implementing such systems, combined with the effective management of FA, can greatly enhance the resilience of urban areas to flood risk.

Overall, there is an urgent need to take action in countries where the urban flood risk is prevalent and has not been effectively addressed. Collaboration between relevant professional groups is critical to developing effective flood mitigation strategies, including implementing NBS and integrated sustainable urban drainage systems. The prioritization of such systems in areas with high FA can help mitigate the risk of urban floods, improving the resilience and safety of urban living areas.

4.3 Limitations

The results of this study must be evaluated considering several important limitations that may impact the validity and generalizability of the findings.

It is important to note that while the Eastern scenario had the lowest average values for both runoff and FVI, this result should not be interpreted as an indicator of the optimal scenario for reducing runoff and flood vulnerability. Other scenarios may have

outperformed the Eastern scenario in specific areas or for specific purposes, but these were not considered in this study.

Furthermore, the study relied on a simplified representation of hydrological processes and land use configurations. It did not consider other important factors that may influence flood vulnerability, such as infrastructure, land use planning policies, and demographics. It is essential to consider these factors in future studies to gain a more comprehensive understanding of flood risk and the most effective mitigation strategies. Additionally, using a single method for quantifying flood vulnerability in this study may not have captured all of the complex interactions and feedback between the different drivers of flood risk, and alternative methods may have provided different results. This highlights the importance of considering a range of methods and perspectives when analyzing flood vulnerability and developing strategies for reducing it.

Finally, the scope of this study was limited to the urban environment of part of a neighborhood in Izmir. It may not accurately represent the conditions in other regions or cities. The findings of this study are related to the study area and cannot be assumed to be directly applicable to other regions without further investigation and analysis. The results and conclusions drawn from this study may not accurately reflect the reality of other cities with different geographic, climatic, socio-economic and cultural conditions. Considering each region's unique features and characteristics is crucial before generalizing this study's results to other areas. This study serves as a valuable contribution to the existing literature on urban flood risk mitigation, but further research is needed to expand the findings to a broader context.

Given these limitations, it is recommended that future research should consider a more comprehensive dataset and a wider range of methods for quantifying flood vulnerability in order to understand better the complex relationships between land use configurations, hydrological processes, and flood risk. This will require a collaborative effort between researchers, practitioners, and policymakers to develop and implement more integrated and comprehensive approaches to flood risk assessment and management. Future research could further explore the potential of ecosystem service modeling approaches in urban planning and climate resilience and the effect of land use change on soil characteristics and hydrological processes.

5 Conclusion

In conclusion, this study aimed to investigate the impact of varied land use configurations on runoff vulnerability in the Karsiyaka district of Izmir, Türkiye. Using the InVEST model and an analysis of FA, we have demonstrated that the hydrologic characteristics of the soils have a greater impact on flood vulnerability than FA. Our findings have important implications for urban planning and resilience efforts, as they highlight the importance of considering soil characteristics when designing land use plans and implementing mitigation measures. Furthermore, this paper simulated the runoff reduction effect of different arrangements to find an optimal strategy for city planning for urban stormwater treatment. The method used in the manuscript is more effective than traditional hydrology models in simulating and comparing the results of many other city planning scenarios since it requires fewer data and effort to run. This means that it could be used for land-use

optimization for green space allocation and policy making. Overall, this study provides valuable insights for decision-makers in urban planning and flood management. Further research could explore the potential of ecosystem service modeling approaches in urban planning and flood resilience.

As we delve deeper into the interplay between land use and flood vulnerability, one factor shines brighter than the rest - soil structure. In crafting urban flood management strategies, it's imperative to have a comprehensive understanding of the soil and its drainage capacities. When mapping out the blueprint of a city, the land structure, encompassing both soil and topography, must be an integral part of the equation and considered in tandem with NBS. Though our study relied on simplified simulations, its findings shape planning dynamics and guide decision-making processes toward a more resilient future.

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The Evolution of Natural Capital Accounting: From Origins to System of Environmental-Economic Accounting

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Abstract. The valuation of natural capital has become an increasingly important issue in the environmental debate and in public policies, given the growing awareness that human well-being depends on the health of terrestrial ecosystems and their services. Natural Capital Accounting (NCA) proposes a solution to measure and value the ecosystem services provided by natural systems, integrating them into economic decision-making processes. However, the wide range of ecosystem resources and services that our natural environment provides is often overlooked or taken for granted, leading to unsustainable practices and the degradation of natural resources. This research proposes an analysis of the evolution of natural capital accounting over time, examining the origins, significant developments and achievements of the approach, with a focus on the methodologies and tools applied. The System of Environmental-Economic Accounting (SEEA) is an important tool for putting this recognition into practice, providing a standardized and coherent approach to measuring and evaluating natural capital. SEEA enables the identification of trade-offs and synergies between economic and environmental objectives and supports the development of policies and practices that promote sustainable development, ensuring the sustainable and equitable use of natural resources. The paper highlights the potential of the SEEA approach to provide useful results and support effective decision-making, emphasizing the importance of considering natural capital as a key element that can be integrated into policy strategies and spatial planning.

Keywords: Natural Capital Accounting (NCA) · Ecosystem Services (ES) · System of Environmental-Economic Accounting (SEEA)

1 Introduction

The growing awareness that human well-being depends on the health of terrestrial ecosystems and their service [1, 2] has developed a new accounting perspective focused on natural capital. Indeed, the valuation of natural capital is an increasingly important issue in the environmental debate and in public policies and urban and territorial

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planning. Despite the wide range of ecosystem resources and services that our natural environment provides, their value is often overlooked or taken for granted, which can lead to unsustainable practices and the degradation of natural resources. Natural Capital Accounting (NCA) proposes an integrated framework to measure and value the ecosystem services provided by natural systems, integrating them into economic decision-making processes [3–7]. In general terms, by assigning an economic value to the components that make up natural capital, such as forests, wetlands, and biodiversity, we can recognize the benefits they provide to society and make informed decisions about their use and management. This, in turn, can contribute to promoting more sustainable practices and ensuring the long-term resilience of ecosystems and the communities that depend on them. Additionally, recognizing the benefits of natural capital can contribute to a greater sense of community and shared responsibility for environmental issues. The System of Environmental-Economic Accounting (SEEA) is an important tool for putting this recognition into practice, providing a standardized and coherent approach to measuring and evaluating natural capital. Ultimately, the SEEA can help identify trade-offs and synergies between economic and environmental objectives and support the development of policies and practices that promote sustainable development, ensuring the sustainable and equitable use of natural resources.

This research proposes, through a review of the literature, an analysis of the evolution of natural capital accounting over time, examining the origins of the approach, its most significant developments and achievements. In particular, we will focus on the discussion of methodologies and tools retrieved in scientific literature and widely adopted to measure natural capital and to integrate this information into traditional accounting systems. The paper is organized as follow: the first section for the analysis of scientific literature, in the second section the SEEA tool is explored in depth.

Conclusions remarks how natural capital accounting can also determine compensation policies that, based on a deterministic approach, can be transposed into land-use regulations.

2 Natural Capital Accounting: An Overall Perspective

However, the concept of capital is understood as a quantity of materials or information existing at a given time, we define by Natural Capital Committee [8] as: “Natural Capital comprises the entire stock of natural assets – living organisms, air, water, soil and geological resources – that provide goods and services of direct or indirect value to human beings and are necessary for the survival of the environment from which they are generated”.

The elements of natural capital fall into two broad categories: biotic (living) components and abiotic (non-living) components. All levels of biodiversity in terrestrial and marine ecosystems are counted within the biotic components, while soil and subsoil (minerals, metals, fossil fuels), water and atmosphere are part of the abiotic components. The last can be both renewable (water, solar energy) and non-renewable (minerals, fossil fuel energy).

Recent researches on Ecosystem Services [9–14] allow us to propose a strong connection between NCA and ES as an operative dimension for applied research. It is

necessary to refer also to the definitions proposed through other disciplinary perspectives. The origin of the concept of capital is to be found in economics. This genesis, in fact, can be found in the writings of economist Alvin S. Johnson, the first to distinguish between artificial and natural capital [15]. Like other forms of capital, natural capital is a stock and not a flow [16]. Costanza and Daly in 1992 [17] defined natural capital as "stocks of natural assets that yield a flow of valuable ecosystem goods or services into the future". The consideration that ecosystem service flows are generated from natural capital has been consolidated over time by different authors [17–21], but their definition and classification is still debated. Regarding the ES definition Fisher et al. [22] indicate that the literature does not have an official and commonly accepted definition, although the one most familiar appears [23] to be the definition provided by Millennium Ecosystem Assessment (MEA) in 2005 [24] that sees ecosystem services as "the benefits that people obtain from ecosystems." Several authors [25, 26] have criticized this definition as too vague arguing that "ecosystem services" are not the same thing as "benefits", as the latter derive from the union of the services offered by nature with other forms of capital. Even the classification is not unique, among the most important worldwide is the one proposed by MEA that divides ES into four broad categories, as follows: 1) provisioning services; 2) regulating services; 3) supporting services; 4) supporting services. However, the scientific literature agrees on the importance of ecosystem services for to the support of human activities, but their importance is often ignored because their value is not easily identified, as they are not tradable on the market. NCA is precisely an approach aimed at measuring, managing and valorising natural capital and its services and is central not only to environmental sustainability, but also to economic, social and spatial sustainability [27, 28]. The last is a transversal dimension of sustainable development, part of a holistic approach to sustainability that takes into account the impact of mankind on the planet. The core definition of sustainable development first introduced in 1987 by the United Nations World Commission on Environment and Development [29] was expanded in 1994 by the International Council for Local Environmental Initiatives, which defines sustainable development as "development that provides ecological, social and economic opportunities to all inhabitants of a community, without creating a threat to the vitality of the natural, urban and social systems that depend on these opportunities". Public decision makers are becoming increasingly aware of the importance of ensuring a more sustainable development, and this is manifested through increased attention to natural resource values. The value of natural capital and its services can hardly be identified through pure economic evaluations alone; it is often necessary to consider nonmonetary approaches. Other authors [30] emphasize the importance of identifying beneficiaries as a dimension for assessing the intensity of the ecosystem service provided. In fact, the main difficulties are due to the confusion that arises over the object of valuation. Costanza et al. in 1997 [18] are among the first to point out that it is not exactly the ecosystem service that is valued, but it is the change in that service or natural capital and that only at a smaller scale will these coincide, whereas as also reported by Toman in 1998 [31] any attempt to estimate the "total value of the world's ecosystem services and natural capital would be a serious underestimate of infinity". Fisher and Turner in 2008 [25] also state that it is the benefits (from combinations of different types of capital) that directly affect human well-being that are valued, so economic valuation rather than

the ecosystem and its services is concerned with the effects that human actions have on them and how these services are employed [23]. In addition, further debates have arisen over which methods to use in valuation. Exchange-value-based methods for ensuring a correct estimate of natural capital benefits have often been criticized. Despite uncertainties about the most appropriate methodology to implement, recent debates on the application of NCA have resulted in different approaches to develop this system in order to integrate it systematically into decision-making processes [32]. Among them is the approach adopted by the United Nations in 2012: System of Environmental-Economic Accounting (SEEA).

3 System of Environmental-Economic Accounting

Many countries are approaching an NCA based on the SEEA [33]. Indeed, SEEA has considerable potential to support decision-making, but despite this, its practical application in public policy delineation is complex [34]. The SEEA was created to overcome the difficulties of conventional Systems of National Accounts (SNA), which are unable to fully and comprehensively consider environmental resources. The purpose of this approach is mainly to combine environmental, economic and social information into single framework that can develop policy relevant indicators to support holistic decision-making. The SEEA framework follows an accounting structure similar to that of the SNA. The choice to use concept, definitions and classification consistent with the SNA is to facilitate the integration of environmental and economic statistics. In 2012 the UN Statistical Commission adopted the SEEA Central Framework (SEEA CF) as an international statistical standard [35]. Measurements provided by it are shown in Table 1.

Table 1. Measurements provided by SEEA Central Framework.

Measurements	Description
Environmental flows	The flows of natural inputs, products and residues between the environment and the economy and within the economy, both in physical and monetary terms.
Stocks of environmetal assets	Stocks of indiviual goods, such as water or energy goods, and the way they change over an accountig period due to economic activity and natural process, both in physical and monetery terms.
Environment-related economic activity	Monetary flows associated with environmet-related economic activies, including expenditure on environmental protection and resource management, and the production of "environmental good and services".

Following the adoption of SEEA CF, the statistical community experimentally proposed SEEA Experimental Ecosystem Accounting (SEEA EEA), designed as a complementary framework to SEEA CF. The conception of the link between the economy

and the environment changes. For while SEEA CF considers how the economy uses natural goods, SEEA EEA instead focuses on ecosystems and the services they provide to economic and human activities. In addition, the SEEA EEA expanded the set of flows considered in the SEEA CF to include ES that provide benefits. Experimentation with the SEEA EEA has found interest in the international community with different projects [36]: Wealth Accounting and Valuation of Ecosystem Services (WAVES), Mapping and Assessment of Ecosystems and their Services (MAES), Integrated System for Natural Capital and Ecosystem Services Accounting (INCA) and Natural Capital Accounting and Valuation of Ecosystem Services (NCAVES). Following a review developed between 2018 and 2020, in 2021 SEEA Ecosystem Accounting (SEEA EA) was approved by UN Statistical Commission. SEEA EA covers two types of accounts in monetary and physical terms: stock accounts and flow accounts. Figure 1 shows that SEEA EA measures [37]: 1) ecosystem extent (usually in spatial units); 2) ecosystem conditions over time; 3) accounts on flows and utilization of ecosystem services in physical terms (for example, tons of sequestered carbon); 4) accounts recording the value of ecosystem services (in monetary terms); 5) ecosystem goods accounts in monetary terms that record the net present value of all ecosystem services provided by an ecosystem good.

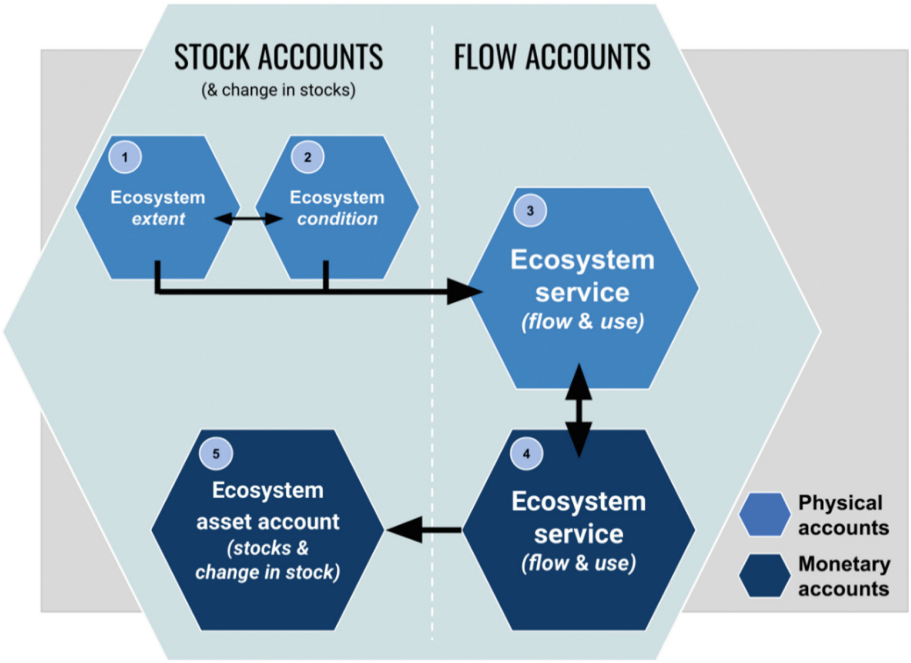

Fig. 1. Connections between the ecosystem accounts. Source: UN [37]

Regarding the monetary valuation of ES flows, the SEEA EA applies the valuation principles of SNA. Ecosystem asset account (in monetary terms) describes both the value of beginning and ending stocks and changes during an accounting period. Variations are

understood as changes in value due to ecosystem conversion, degradation, or improvement, or price changes. Additionally, SEEA EA adopts a spatial approach, since the benefits a society receives from ecosystems depend on where those assets are located in the landscape in relation to the beneficiaries. This approach identifies the location and size of ecosystem resources, the ecosystem services provided and the location of beneficiaries [38–41]. In fact, SEEA EA can be implemented at different spatial scales such as sub-national or national level [42, 43]. As of 2020, 34 countries have compiled ecosystem accounts and another 13 are outlining plans for implementing the SEEA EA. Among them, the European Commission has made public accounts regarding the extent, condition and services provided by ecosystems for the entire EU territory.

4 Final Remarks

The importance of ecosystem services in the scientific world has generated the need to have an effective tool that can provide useful results in research and that will reinforce the proper monitoring and management of ecosystem assets and their flows. SEEA has all the potential to be an excellent tool useful in informing decision making at various stages and supporting numerous policy choices. This approach not only allows natural capital to be considered as a key element to be integrated into policy strategies and spatial planning [44], but also highlights its importance through the economic aspect. Indeed, the framework was created to highlight the impact of the economy on the environment and the environment on the economy. These necessary trade-offs between the environmental, economic, social and also spatial spheres (given the characteristic of the SEEA EA to be a spatial approach) are highlighted through the different indicators that can be generated from the reports provided by the international standard. The difficulties highlighted in the NCA, i.e., unambiguously defining and classifying ecosystem services, identifying tools capable of providing their value (not only in monetary terms) were critical basis for the development of this approach, indeed SEEA can be considered the result of the ongoing effort to have natural capital accounting effectively and efficiently integrated into a decision-making process both at national, regional or local level. In particular, the challenge for its application concerns the local level where it is difficult to find data both on ES and environmental variables and with respect to value streams. New data analytics has to be selected in order to support the quantitative assessment in the territorial perspectives [45–47]. However, the circumscribed identification of beneficiaries and consequently their involvement provides a broadening of the audience of stakeholders involved in the management of environmental protection processes. The possible identification of impacts resulting from production processes that use local environmental resources allows for the maturation of a greater awareness with respect to the scarcity of natural resources and increases the feeling of their protection [7, 48, 49]. The research perspectives looks at: (i) delving into the SEEA framework; (ii) defining significant case studies; (iii) developing a discussion with potential stakeholder beneficiaries of the tool to verify its applicability within decision-making processes involving them.

This paper sought to highlight the process that led to the emergence of SEEA from the NCA and the potential of this tool to support improved policy making that includes the environmental, economic, social, and spatial (referring to recent experience in NUA

downscaling [50–53] dimensions necessary for effective implementation of the cardinal principles of sustainable development [54].

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Assessing the Relation Between Land Take and Landslide Hazard. Evidence from Sardinia, Italy

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Abstract. The process of land-taking and soil sealing involves changing the way land is used, which in turn can make the land more vulnerable to landslides. This means that the land may not be able to withstand the forces of landslides as effectively as it could before. Therefore, this study examines how land-taking processes, such as urbanization, can increase the risk of landslides. The study asks the research question, "To what extent do land-taking processes increase landslide hazard?". The impact of land take is measured using a regression model that analyzes land cover variables, including artificialized land, and other land cover types grouped according to the LEAC (Land and Ecosystem Accounting) classification. The study is conducted in Sardinia and shows that land-taking processes, including urbanization, increase the size of the area prone to landslides. The study offers suggestions for planning policies to mitigate the impacts of land cover transitions on landslide hazards.

Keywords: Land Take · Landslide Hazard · Land Cover Change

1 Introduction

As per the European Environment Agency, "Land take is the process in which urban areas and sealed surfaces occupy agricultural, forest or other semi-natural and natural areas" [1] (p. 117). At the end of 2021, the European Commission approved a new Soil Strategy for 2030, which highlights how healthy soils are essential for achieving the objectives of the European Green Deal concerning climate and biodiversity. The strategy defines a general framework and concrete measures to protect and restore soils to ensure their sustainable use [2]. One of the long-term objectives to be achieved by 2050 is to reach "no net land take" [2] (p. 3). The general framework of the strategy termed "land take hierarchy" concerns four consequential actions, which are prioritized as follows: avoid, reuse, minimize, and compensate. Prioritization means that the lower level should be implemented when implementing the higher level is impossible. In this context, "Avoid" aims at preventing further land take; "Reuse" means re-using land that has already been urbanized or sealed; "Minimize" refers to curtailing the effects of land

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take by impermeabilizing land already in unfavorable conditions; "Compensate" entails applying compensation and mitigation measures. The main causes of land take are to be attributed to expansion of industrial and commercial areas, and to enlargement of residential zones and construction sites [3]. Land-taking processes entail several problems, such as the loss of multifunctional and fertile soils, biodiversity degradation and loss of ecosystem services (ESs), that is, benefits provided by ecosystems to human beings, including protection against hydrogeological hazards such as floods and landslides [4].

A landslide is the movement of materials such as rock, soil, debris, and artificial fill. Landslides primarily occur in mountainous areas, but also in low-relief zones, and can have geological, morphological, or artificial origins. Natural causes include the intrinsic properties of rocks and soils, as well as physical processes, such as heavy rains and seismic activity; artificial causes include changes in slope stability brought about, for instance, by deforestation or excessive soil sealing [5]. Therefore, landslides can be strongly connected with land use and land cover dynamics [6] and, particularly, with human-driven processes [7], such as land use/land cover changes, which alter vegetation and modify soils and hydrogeological processes [8, 9]. Land use/land cover changes can influence landside events due to their potential impacts on hydrological and mechanical processes involving soils [10, 11].

The relation between land use/land cover changes and landslides has been studied by various authors [among many: 7, 12, 13]. However, the relation between land-taking processes and landslide hazard is still under-researched. Therefore, such relationship is here explored in order to understand to what extent land-taking processes increase landslide hazard through a regression model that relates the level of landslide hazard to a set of land cover variables that includes artificialized land. The methodological approach is implemented in the Sardinia Region, Italy.

The study is structured into six sections as follows. The second section describes the study area, the methodological approach used, and the input data for the regression model. The results are presented in the third section and discussed in the fourth section. The fifth section provides recommendations and implications for spatial planning policies stemming from the results, while the sixth section provides concluding remarks and future directions of the research.

2 Materials and Methods

2.1 Study Area

The so-called "Coghinas-Mannu-Temo" subdistrict (hereafter, CMT), is the area chosen for this study (Fig. 1). It is one of the river basin districts in which the island of Sardinia, in Italy, was subdivided, and it is made up of around forty watersheds, of which the largest and most important ones are the four ones from which its name originates, i.e., Coghinas River, Mannu River, Mannu River in Porto Torres, and Temo River. The reasons for choosing the Sardinian CMT subdistrict for this study are twofold. First, Sardinia is included in the CORINE Land Cover (CLC) inventory coordinated by the European Environment Agency under the Copernicus program of the EU; this makes it possible to retrieve a regularly updated series of land cover maps, of which the most recent one refers to the year 2018 [14]. Second, a comprehensive and detailed spatial assessment

of landslide hazard and risk concerning the whole CMT was carried out and officially validated in 2014 [15] and it is publicly available from the regional geoportal.

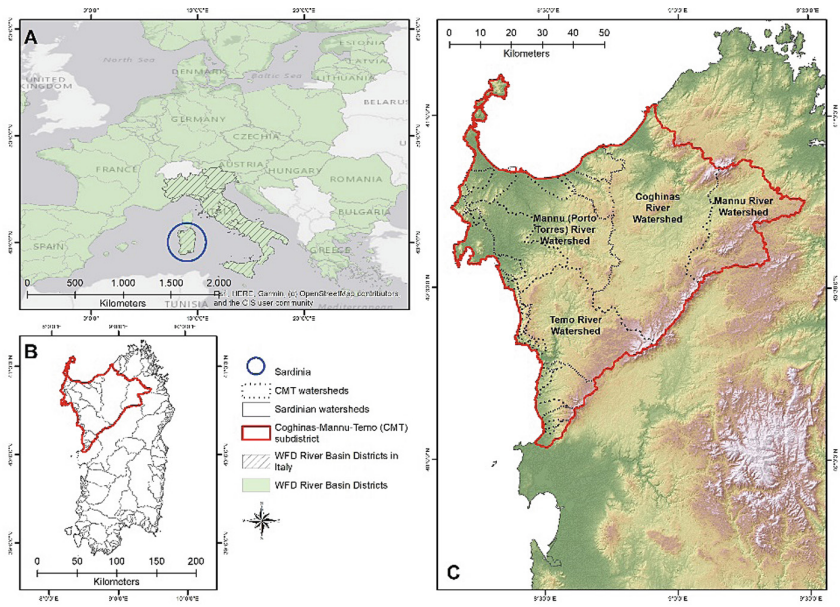

Fig. 1. River basin districts in Italy (panel A), Sardinian watersheds (panel B), and the Coghinas-Mannu-Temo subdistrict with its watersheds (panel C).

The prevailing morphology within the CMT is hilly, the climate is typically Mediterranean, and the vegetation is characterized by the cork tree series and the holm oak tree series. Geological instability is diffuse in the study area, where landslide events have been recorded for decades: the Italian landslide inventory (IFFI [16]) has documented 398 landslide events occurring up to 2007 in the CMT. The most prominent category is that of diffuse falls or topples, followed (in order) by simple falls or topples, by diffuse superficial instability, and by rotational or translational slides.

2.2 Regression Model

The relation between landslide hazard (LH) and the size of land taken up (L_TAKE) is assessed through a linear regression model that uses the LEAC land cover groups as explanatory variables, whose definitions are given in Sect. 2.3. The covariate representing land take is one of the LEAC groups, namely the variable associated with the artificialized land LEAC group. Dependent and explanatory variables refer to the elements of a 300-m square grid that overlays the study area, and are measured as their percentage share of a grid cell. The model operationalizes as follows:

$$\begin{aligned} \mathrm{LH} = {} & \alpha_0 + \alpha_1 \mathrm{L_TAKE} + \alpha_2 \mathrm{ARA} + \alpha_3 \mathrm{PMF} + \alpha_4 \mathrm{FOR} + \alpha_5 \mathrm{GRSH} + \alpha_6 \mathrm{DEPOQ} \\ & + \alpha_7 \mathrm{VOLSE} + \alpha_8 \mathrm{ELEV} + \alpha_9 \mathrm{HGLAGGED} \end{aligned} \quad (1)$$

where the dependent variable and covariates are identified as shown below.

- LH is for landslide hazard.
- L_TAKE is for artificialized land or land take.
- ARA is for arable land.
- PMF is for pastures and mosaic farmland.
- FOR is for standing forests.
- GRSH is for natural grasslands, sclerophyllous vegetation, and heathlands.
- DEPOQ is for ground substrate characterized by quaternary deposits.
- VOLSE is for ground substrate characterized by volcanic sedimentary rocks.
- ELEV is for the average elevation of a grid element.
- HGLAGGED is the spatially lagged dependent variable that controls for spatial autocorrelation of LH.

The estimates of the coefficients of the multiple linear regression show the correlations between landslide hazard and the land covers of the LEAC taxonomy and, in particular, the interdependence of LH and the size of land take.

The use of a multiple linear regression is motivated by the fact that prior assumptions are not available as regards the functional form of the relations between dependent and explanatory variables, which is consistent with several studies aimed at identifying the interdependence between spatial variables [17]. From this point of view, a spatial phenomenon, related to n variables, represented by a surface in an n-dimensional space whose equation is unknown, can be approximately detected, in each of its points, by the tangent hyperplane. The linear equation estimated through the regression model, which relates dependent and explanatory variables, identifies the tangent hyperplane in a small neighborhood of a point of the surface, and in such neighborhood it represents an approximation of the unknown equation of the surface [18]. Hence, model (1) represents the trace of a hyperplane on a surface in a ten-dimensional space, which reports the correlations between LH and the nine covariates listed above.

The covariates DEPOQ and VOLSE control for the ground substrate, by considering if, and to what extent, landslide hazard is influenced by the conditions of the substrate, which in the study area is mainly featured by cohesive and compact rocks such as volcanic sedimentary successions (VOLSE) and, secondly, by deposits from the quaternary era (DEPOQ), i.e., loose incoherent materials. ELEV controls for the altitude impact on landslide hazard. If the estimates of their coefficients in (1) are significant, this will entail that substrate and elevation are likely to influence LH, at least to some extent. The magnitude of the coefficients will show the size of the impacts, in terms of increase or decrease in the landslide hazard measure.

The sign of ELEV is expected to be negative, since in the study area, on average, landslide hazard conditions are more frequent in lowlands rather than in mountainous locations, as further discussed in Subsect. 3.3, whereas the expected signs of DEPOQ and VOLSE are positive and negative, respectively, since it is intuitively likely that LH will increase as long as the substrate incoherence and looseness increases, and the other way around. The variable HGLAGGED represents the spatially lagged values of LH, and controls for spatial autocorrelation of the dependent variable in model (1). The HGLAGGED definition builds on Anselin's work [19].

Moreover, a p-value test is used to check the level of significance of the estimates of the coefficients of model (1).

2.3 Input Data for the Regression Model

The dependent variable and covariates needed to feed into the regression model (1) were calculated with reference to a 300-m vector square grid that covers all of the CMT subdistrict and comprises a total of 62,231 cells, using four main input spatial datasets listed in Table 1.

Landslide Hazard. Landslide hazard levels in the study area were assessed in 2014 within a study commissioned by the Sardinian Basin Competent Authority in 2011, whose documents are publicly available on the institutional website [15]. As per the methodology used in the PAI, landslide hazard (HL) classes range in the 0–4 interval, as follows: no hazard: HL = 0; moderate hazard: HL = 1; medium hazard: HL = 2; high hazard: HL = 3; very high hazard: HL = 4. For each cell in the 300-m square grid, the dependent variable LH in model (1) was calculated as the percentage of the cell's area having non-null landslide hazard (HL $\neq$ 0) in the vector data retrieved from the geoportal. Moreover, LH's spatially lagged variable (HGLAGGED), included in model (1) as a covariate, was calculated using GeoDA (version 1.20) [20].

Table 1. Input datasets used to compute dependent and explanatory variables.

Input Datasets	Sources	Link
Landslide hazard	Regional geoportal	https://webgis2.regione.sardegna.it/geonetwork/srv/ita/catalog.search#/metadata/R_SARDEG:eb38d6c0-b51f-4df1-acdc-f7a752e7664c
LEAC land cover groups	Copernicus—Europe's Eyes on Earth program	https://land.copernicus.eu/pan-european/corine-land-cover/clc2018
Elevation	Regional geoportal	https://www.sardegnageoportale.it/areetematiche/modellidigitalidielevazione
Geological characteristics	Regional geoportal	https://www.sardegnageoportale.it/index.php?xsl=2420&s=40&v=9&c=14479&es=6603&na=1&n=100&esp=1&tb=14401

LEAC Land Cover Groups. In this study the 2018 CORINE Land Cover vector map (CLC2018) was used. The map provides information on land covers, i.e., on the biophysical characteristics of the Earth's surface, through a hierarchical classification that

comprises 44 classes at the third (and lower) level, 17 at the second level, five at the first level, with a minimum mapping unit equaling 25 hectares. The CLC2018 was next reclassified so as to group the third-level land cover classes following the taxonomy used by the European Environment Agency for land cover accounts [21] and comprising eight groups. Detailed information on how the reclassification was performed is provided in [22].

Geological Characteristics and Elevation (Control Data). A 1:25,000 regional geological map of Sardinia was produced at the beginning of the year 2000 building upon geological data collected by the former regional agency for mines and quarries. The spatial dataset, available from the regional geoportal [23], identifies geological characters in compliance with the "CARG" national mapping program initiated in the 1980s by the Italian Geological Society. The taxonomy of the Sardinian geological map is hierarchically structured into five main classes and five levels ([24], pp. 49–108), and a simple reclassification was carried out in this study, whereby i., first-level classes only were considered and, ii., three main groups were retrieved by merging first-level classes. The three groups are as follows: i., quaternary deposits (also comprising lakes); ii., volcanic sedimentary successions; iii., intrusive complexes and metamorphic basements. Finally, for each cell in the 300-m square grid, the explanatory variables DEPOQ and VOLSE were calculated as the shares of the cell occupied, respectively, by quaternary deposits and by volcanic sedimentary successions. For any terrestrial cell in the grid, the share occupied by the third group is, fairly obviously, the difference between 100 and the sum of DEPOQ and VOLSE.

Elevation was retrieved from the 10-m resolution digital terrain model (DTM) available "off the shelf" from the regional geoportal [25]: for each cell in the 300-m square grid, the explanatory variable ELEV in model (1) was calculated as the average elevation in the cell.

3 Results

3.1 Landslide Hazard in the Study Area

In the vast majority of CMT (i.e., 80.29% of the CMT land mass) the hazard level was assessed as null by the PAI, while around a fifth of the subdistrict is prone to landslides, mostly of medium (10.40%) or high severity (6.67%); a very small share of the CMT (1.92%) features moderate landslide hazard and a negligible one (0.71%) is characterized by very high hazard levels. Within the 300-m grid used in this study, LH is greater than zero in 30,775 out of the total 62,231 300-m grid cells (Fig. 2, panel B); hence, in nearly half of the cells, landslide hazard, of whichever level, affects a certain share of the cell.

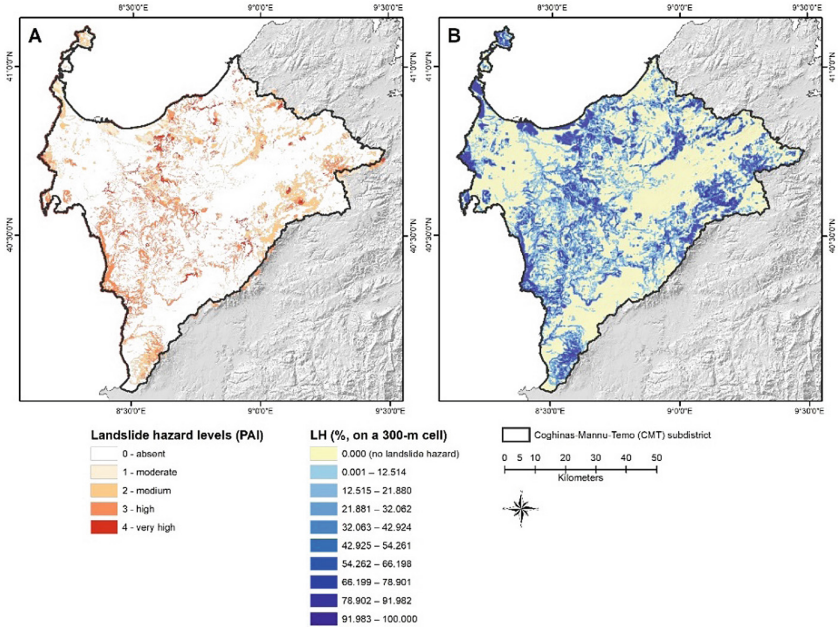

Fig. 2. Landslide hazard levels as assessed by the regional PAI in the CMT subdistrict (panel A), and spatial distribution of the LH variable in the 300 m grid used in this study (panel B).

3.2 The Spatial Framework of the LEAC Groups

Three LEAC groups prevail in the CMT subdistrict, as shown in Table 2 and Fig. 3: arable land and permanent crops (32.09%); pastures and mosaic farmland (26.68%); natural grasslands, sclerophyllous vegetation and heathlands (23.19%). Together, they make up 81.96% of the study area. Next come standing forests (14.98%), while artificialized land amounts to 2.37% of the study area, and a negligible share (0.69%) is that of waters, which are not listed in Table 2 because they were not relevant for this study.

Table 2. LEAC groups as share of the Coghinas-Mannu-Temo subdistrict.

LEAC Groups	Area (% CMT)
Artificialized land (land taken by development)	2.37
Arable land and permanent crops	32.09
Pastures and mosaic farmland	26.68
Standing forests	14.98
Natural grasslands, sclerophyllous vegetation, and heathlands	23.19

Panels B-F in Fig. 3 show the spatial layout of the share of each LEAC group in the 300-m grid cells used within this study. Cells having non-null values of L_TAKE

form small and spatially disarticulated bundles. Cells where a share of arable land and permanent crops (ARA) is present cluster especially along the main plains; however, they are spread across the subdistrict, except for the Asinara Island to the north and the mountain areas that delineate the borders of the watersheds. In the latter, clusters of cells hosting standing forests (FOR) are clearly visible in the map, while the Asinara Island is a hotspot for natural grasslands, sclerophyllous vegetation, and heathlands (GRSH), which also feature along the rugged western coast and are scattered across CMT. Finally, cells hosting pasture and mosaic farmland (PMF) are diffuse across the subdistrict, with the larger assemblage along the Marghine mountain chain to the southern border.

3.3 The Outcomes of the Regression Model

The strength and significance of correlations between the explanatory variables in model (1) were preliminarily assessed through the Pearson product–moment correlation coefficient. The outcomes of this assessment, which was carried out on the attribute table of the shapefile containing the 30,775 cells having non-null values of LH, show that the strongest correlation is that between PMF and GRSH (-0.4033, $p < 0.01$), while $|r| < 0.4$ for the remaining couples of variables. The lack of strong correlations between the explanatory variables highlights the absence of issues of multicollinearity in model (1).

The estimates of the coefficients of DEPOL and VOLSE are significant and show the expected signs, since comparatively higher values of LH are associated with the incoherent and loose substrates that characterize quaternary deposits, and comparatively lower LH values are correlated with the solid and resistant substrates that feature volcanic sedimentary rocks. Moreover, lower altitudes are associated with higher landslide hazard, and a decrease of 100 m is correlated with an increase of 1.8% in landslide hazard. While this outcome may seem counterintuitive, the reason lies in the peculiar spatial taxonomy of landslide hazard in the study area, where high-landslide-hazard zones are concentrated in locations characterized by comparatively low and medium elevation. Finally, as regards the control variables, the spatially lagged variable shows a positive and significant sign, in terms of p-values, which shows an effective control of the spatial autocorrelation of the dependent variable.

The estimated coefficients of the five explanatory variables are significant at 1% and entail the following results, provided that everything else is equal.

Agricultural land, whether characterized by extensive or intensive production, is negatively associated with landslide hazard, showing comparatively low correlations, since, on average, a 10% increase in pastures and mosaic farmland or in arable land corresponds to a 0.7% decrease or to a 1% decrease in landslide hazard.

Positive correlations are shown by the coefficient of FOR, since 10% increases in FOR and GRSH are associated with 1.4% and 0.9% increases in LH, respectively. Increases in forests, natural grasslands, sclerophyllous vegetation, and heathlands are associated with higher values of LH, which entails that such land covers are likely to identify buffer zones with respect to areas characterized by relevant landslide hazard. The spatial contexts featured by these land covers are usually almost totally devoid of human settlements, which highlights a virtuous spatial organization, which aims at protecting urbanized areas from the negative impacts generated by landslides, by preserving natural forests and grasslands from land-taking processes.

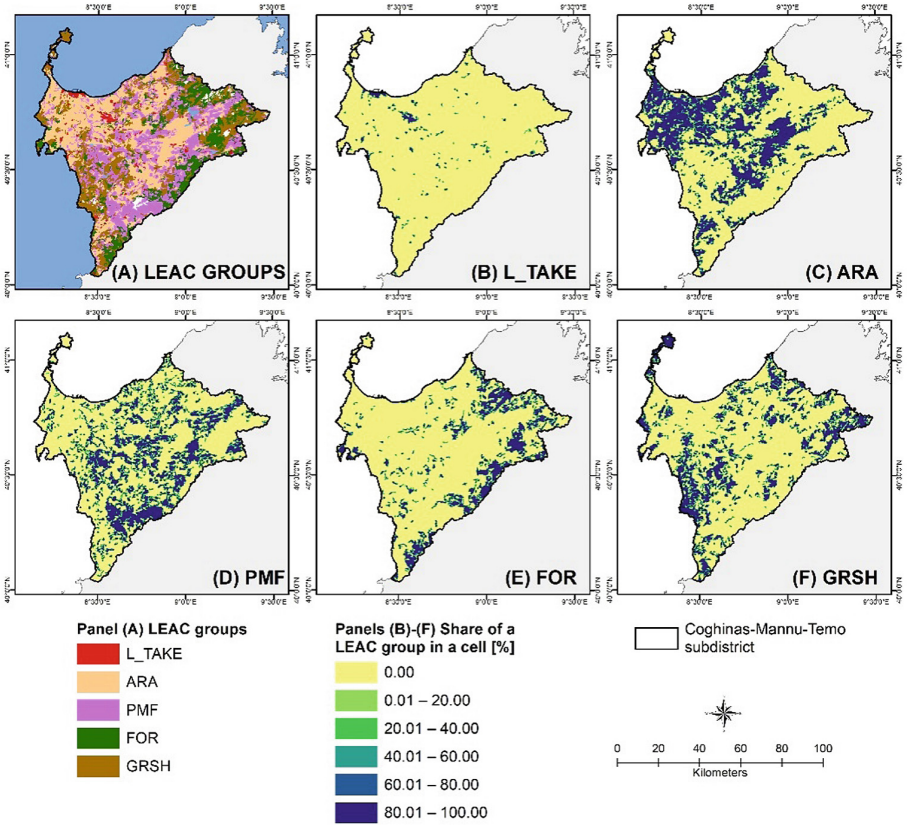

Fig. 3. Spatial distribution of land covers in CMT classed through the LEAC groups (panel A), and share of each LEAC group within the 300 m grid used in this study (panels B, C, D, E, F).

All in all, crop production is not associated with increases in LH. On the other hand, forests are the LEAC group that reveals the most relevant positive correlation with landslide hazard, whereas natural grasslands, sclerophyllous vegetation, and heathlands are less relevant in terms of association with LH.

Finally, the regression model identifies the association of LH and L_TAKE as a relevant positive correlation; namely, a 10% increase in L_TAKE is associated with a 0.8% increase in LH. In other words, the higher the size of the land take-related covariate, the higher the size of areas characterized by relevant landslide hazard. This finding highlights that the spatial structure of the study area is characterized by artificialized areas intertwined with areas featured by relevant landslide hazard, or that land-taking processes have taken place in locations that should have been preserved free from urbanization processes due to the magnitude of landslide hazard. Table 3 reports the results of the estimate and relevant statistics of regression model (1).

Table 3. Estimate of regression model (1).

Variable	Coefficient	t–Statistic	p–value
ARA	−0.10613	−11.28802	0.00000
PMF	−0.07235	−7.81156	0.00000
FOR	0.14146	14.72390	0.00000
GRSH	0.09436	10.44108	0.00000
L_TAKE	0.08803	5.85287	0.00000
DEPOL	0.01569	1.68502	0.09201
VOLSE	−0.07308	−15.41213	0.00000
ELEV	−0.00978	−10.60318	0.00000
HGLAGGED	0.96762	23.96984	0.00000
Adjusted R-squared: 0.83247			

4 Discussion

The mapping of landslide hazard in the study area is quite consistent with the taxonomies of similar spatial contexts described and discussed in the current literature. Hilly spatial contexts intertwined with plain areas, such as the CMT, are often associated with limited zones characterized by relevant landslide hazard and by diffused geological instability, as demonstrated by the regional screening of landslide phenomena in the lowlands of Calabria, Southern Italy [26]. The European screening study by Jaedicke et al. [27] identifies the European hotspots concerning landslide hazard, based on the implementation of the models defined by the International Center for Geohazards (ICG) and the Joint Research Center of the European Commission (JRC), which are often located in hilly and plain areas, i.e., with morphological characteristics similar to the CTM subdistrict, sometimes featured by high levels of precipitation and seismic activity. The European screening is quite consistent with what was detected in the case of the landslide inventory implemented by Solís-Castillo et al. [28] as regards the Mexican tropical region of Sierra Costa, characterized by low precipitation rates and landslide hazard diffused over mountainous and plain zones. Analogous findings are shown in many recent studies (among which [29] and [30]).

The spatial distribution of the LEAC groups in the study area is consistent with the spatial taxonomies reported in other studies concerning landslide hazard in hilly spatial contexts intertwined with plain areas. As in the case of the CTM subdistrict, important relations between landslide hazard and farming production in hilly and plain zones have been identified in the literature [31]. Landslide hazard and related events in hilly spatial contexts intertwined with plain areas are mainly related to soil erosion phenomena [32], which should be addressed by increasing soil retention capacity [26], and the endowment of ecosystem services such as ground and superficial water resources quality and recharge, ground and underground biodiversity, and soil resilience to the impacts of climate change and of landslide events [33].

The outcomes of the regression model can be straightforwardly discussed in the theoretical and technical context of the current literature.

Negative correlations are associated with agricultural land, whether it is characterized by intensive or extensive crop farming. This is consistent with the results of several studies which relate the effectiveness of soil conservation practices based on agriculture (among many, [34]). In particular, the mapping of the quoted study by Santangelo et al. [34] is consistent with the regression outcomes related to the covariates that identify forests (FOR), and natural grasslands, sclerophyllous vegetation, and heathlands (GRSH). Since the latter two LEAC groups characterize non-urbanized areas, it has to be put in evidence that a virtuous approach to land use planning brings together Central Italy and the Sardinian CMT subdistrict, since areas with relevant landslide hazards have been kept almost totally settlement-free.

The outcomes related to the DEPOQ covariate are consistent with previous studies [35, 36], where significant landslide hazard is correlated to inland wetlands, whereas coastal wetlands are associated with low LH, which brings together the CMT and the Central Italy coastal wetlands, as characterized by Santangelo et al. [34].

As for forests, woodlands, and shrubs, not only do they almost totally feature the non-urbanized areas of the CMT district, but also, they act as spatial contexts whose management is crucial to implement planning policies aimed at decreasing the environmental risk associated with landslide hazard. The enhancement and strengthening of forests and woodlands is related to the protection of primary forests, to forest recovery activities, to sustainable management of forests and woodlands, and to tree planting in spatial contexts characterized by different prevailing ecosystems, such as urban and agricultural areas, where these LEAC groups play a decisive role in mitigating the impact of landslide hazard [37]. FAO identifies forest sustainable management as the most important operational category to enhance economic, social, and environmental quality of rural areas, mainly because of its impact on improvement of crop production and productivity connected to protection from flood and landslide effects [38]. Forest and woodlands' recovery and new arboreal plantations are particularly relevant for the definition and implementation of spatial planning policies since the assessment of their economic impact in terms of mitigation and adaptation to climate change is generally recognized as particularly effective in the medium and long runs, especially due to decrease in flood and landslide risk [39], as well as for biodiversity protection and enhancement [40].

Finally, the regression model shows that landslide hazard is significantly associated with land take in the CMT subdistrict. This finding is supported by the fact that the other results of the regression are consistent with the outcomes of several studies available in the current literature, which implies that the definition and implementation of spatial planning policies aimed at addressing landslide hazard in the study area are almost entirely an issue of countering the ongoing land-taking processes and of deurbanizing at least a part of the areas located in landslide-prone zones. This is a key issue in the current scientific and technical debate (among many, [41, 42]), and it is widely discussed in the fifth section.

5 Policy Implications

The results show a positive correlation between coefficient of FOR and landslide hazard due to virtuous spatial organization aimed at protecting urbanized areas and at preserving natural forests and grassland from land-taking processes. Forests have positive effects on reducing impacts of landslide. In shallow soils, deep-rooted trees and shrubs may reduce the occurrence of rapid landslide, while trees may represent a physical barrier to contrast rocks and debris. Two main policy implications can therefore be identified as follows. First, forest management should consider the potential of forests and woodlands for landslide protection by restoring and protecting natural forests [43] and by maintaining forest cover. Secondly, spatial planning should localize forest in high-risk areas in order to support a virtuous spatial organization that locates human settlements and activities in zones characterized by low levels of landslide hazard.

The most prominent result is, however, the significant positive correlation concerning L_TAKE; therefore, as far as land covers and their effects on landslide hazard are concerned, controlling land-taking processes is the main road to mitigating the hazard. On this premise, three main groups of policy implications, respectively concerning land densification, land recycling, and strategic environmental assessment, can be identified as follows.

As for land densification, it implies that land is developed within existing settlements so as to take advantage of existing infrastructure without using undeveloped land [44], Therefore, national and regional administrations should promote land recycling strategies within regional plans, to be further downscaled at the local level through municipal masterplans where new development should be allowed only if its impacts on land take are negligible. Moreover, regional strategies should promote a compact urban model based on the land densification concept to reduce demand for undeveloped areas. However, this should not be regarded as a "one size fits all" solution, as local specificities need to be taken into account. Indeed, such measures have been found to be particularly effective in developed countries, whereas in Latin America and Sub-Saharan Africa, as well as in already hyper-dense Asian megacities, further urban densification can bring about negative effects in terms of inequality of spatial distribution and social conditions of the local communities [45].

With regard to land recycling, this is mainly supported through financial and regulatory tools. Concerning the former, financial support through publicly funded programs [46] and subsidies generated through impact fees, soil sealing fees, or improvement levies [47] are among the most common tools to promote land recycling. However, national and regional governments should diversify the set of fiscal tools that usher in creative and innovative ways to manage land uses effectively and efficiently. For example, the transfer of development rights can be used to direct development towards already taken up and well-serviced areas, rather than towards greenfield areas that are poorly connected in terms of transport, infrastructures, facilities, and services. As for regulatory tools, such as zoning schemes and land use regulations, these could successfully promote the participation of the private sector within land recycling projects. Furthermore, flexible and performance-based zoning regulations could be adopted within municipal masterplans [48]: these should pursue strict limits and constraints on land take, while allowing land uses that do not result in artificial land, hence in turn promoting mixed land uses where

different functions coexist. Due to the complexity of interests at stake, measures concerning land-take prevention and limitation, be they finance-based or regulation-based, call for active involvement of local communities and municipalities [49], and for effective vertical and horizontal cooperation between governments and other public bodies [50].

A third important policy implication concerns strategic environmental assessment (SEA), an appraisal planning tool that is mandatory in EU countries, which ensures that environmental considerations and sustainable-oriented goals are integrated into plan-making processes by assessing their likely effects on the environment, by considering reasonable and more sustainable alternatives, and by taking into account the mutual relations between the environment and the economic and social sectors [50]. Through the comparison of alternative land uses, the identification of areas that are more suitable for certain uses, and the evaluation of cumulative, direct, and indirect impacts of land-based investments, SEA can pave the way for the integration, within spatial plans, of measures aimed at preventing or minimizing land take.

In areas prone to landslide hazard (as well as in areas prone to flood hazard, which are not the object of this study), in Sardinia the PAI maps serve as a spatial reference for the PAI regulations, which restrict land uses and prevent land transformations depending on the magnitude of the hazard. In this way, the PAI provides a legally binding framework for municipal masterplans, whose zoning choices must comply with the PAI regulations, contrary to what has been reported in other countries [51], where new development in landslide hazard areas is not prohibited [52]. Hence, this higher-level regional planning tool contributes to limiting land-taking processes in fragile areas, while also providing relevant spatial information to planners in charge of drafting land use plans and appraising them through the SEA. Moreover, because the PAI maps are publicly available through the regional geoportal, they also contribute to raising local authorities' and local communities' awareness of landslide hazard and, by doing so, to granting transparency and legitimacy to restrictions that otherwise would be, in principle, quite conflictual.

6 Conclusions

In this study a novel methodological approach was proposed with a view to analyzing the relations between land-taking processes and landslide hazard in order to understand whether, and to what extent, land-take phenomena are associated with landslide hazard. The outcomes of this analysis were next used to define policy suggestions that, by preventing or minimizing land take, can help mitigating landslide hazard, therefore indirectly preventing the human and economic losses that might result from land mismanagement. The methodological approach here proposed as a tool to support decision-making processes can be exported to other European contexts, since the CLC inventory is available for 39 European countries [14], among them the 27 EU Member States, provided that a detailed landslide hazard or landslide susceptibility spatial dataset is available, which is not the case for all of the EU Member States, as reported in a recent study by Mateos et al. [51].

Moreover, the methodological approach shows a certain degree of flexibility, allowing for the inclusion of further context-specific spatial or normative variables that might

be appropriate or needed in other contexts. In our selected case study, the influence of two LEAC groups (open space with little or no vegetation; transitional woodland and shrub) on landslide hazard could not be assessed because they were not relevant in the study area, hence this might be a matter for future investigation in other contexts. In addition, the impact of specific land cover classes on landslide hazard was here not assessed due to the simplified classification of the LEAC taxonomy, where the 44 CORINE land covers are aggregated into eight groups. Future directions of the research might therefore include a more detailed analysis, where the LEAC groups are (completely or partly) replaced by the CLC classes, which might, however, result in a more complicated implementation of the model and interpretation of its results.

This study has analyzed the relations between land-taking processes and landslide hazards in a cross-section terms; therefore, dynamic issues, such as the evolution process of land covers or the development through time of different forms of urbanization are not within the scope of this work. However, these are relevant future directions related to the research work proposed in this article, which may entail the assessment of the dynamics of the relationship between landslide hazard and land-taking processes. The advantages in analyzing how land cover changes are correlated to landslide hazard are connected with the outstanding dynamicity that characterizes land cover change processes. Although different factors influence landslide hazard in the long run, such as geological and geomorphological phenomena, land covers are also characterized by short-term dynamics, which stresses the relevant added value which may be provided by a time-series-based contextualization of the cross-section assessment here implemented. As regards the dynamic relationships between urbanization processes and landslide hazard, further important research directions are represented by the assessment of landslide phenomena in different cities and towns characterized by diversified urban morphologies, ranging from dense and compact urban fabrics to sparse and widespread urbanization, in order to define and implement planning policies and measures aimed at countering and mitigating landslide hazard.

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GeoAI Approach for Analyzing Territorial Specialization in Ecosystem Services Provisioning

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Abstract. The ecosystem services (ES) framework is an emerging topic addressing the issue of promoting sustainability in planning. One of its strengths is its ability to facilitate spatially explicit assessments, which can help elicit conflicts between human and nature in a functional perspective. This study aimed to exploit the informative potential of the ES framework to produce new geographies of the territory based on a formal and quantitative assessment of different levels and categories of territorial specialization in ES provisioning, using innovative geoAI techniques. The research was based on previous studies where ES supply had been computed at the national level and tested on a sample area. The study area included several environmental challenges, socio-economic underdevelopment, and potentials in the tourism sector. The paper discusses how the integration of ES with machine learning techniques enhances the informative potential in spatial explicit classification of a study area. The results show a high degree of spatial interpretation potential derived from the regionalization map in terms of statistical similarity of detected regions. The study concludes by highlighting the need to better define the concept of territorial specialization in ES provisioning to reinforce the methodological proposal extending to other relevant case studies.

Keywords: Ecosystem Services · geoAI · regionalization · spatial planning · unsupervised ML

1 Introduction

Ecosystem Services (ES) refer to the valuable services that nature provides to human societies, such as clean air and water, nutrient cycling, pollination, and climate regulation. It provides a robust methodology for evaluating the tradeoffs associated with land-use transformations, with relevant implication on Green Infrastructures [1, 2] and nature conservation policies [3, 4] and, widely, on the emerging topic of zero land take. ES framework reinforced, even if still not included in the normative planning framework, the monitoring capacity of Public Bodies entitled with competences and responsibilities in planning to detect and quantify land use transformation process [5–7]. The result is an extended potential to inform decision-makers and to let them aware of the costs or benefits

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of these changes, taking into account both the direct and indirect impacts on ecosystem services. The ES framework also enables the identification of complex dynamics between ecosystems and human societies, and promotes communication and joint implementation among stakeholders at different levels of governance [8, 9]. One of the key strengths of the ES framework is its ability to facilitate spatially explicit assessments, which can help identify areas where ecosystem services are most valuable and prioritize conservation efforts. Ultimately, the ES framework promotes sustainability in planning by elicitating the conflicts between human and nature in a functional perspective for humans.

This study is oriented to exploit the informative potential of ES framework in order to produce new geographies of the territory based on a formal and quantitative assessment of different levels and categories of territorial specialization in ES provisioning. In order to achieve this challenging objective the research was based on the application of innovative geoAI techniques according to the need to exploit the informative complexity derived from ES multivariate spatial appraisal without any ex-ante simplification of the information model.

The approach was based on previous studies where ES supply had been computed at national level (Italy) and tested on a wide sample area: the Province of Potenza in Basilicata region. This context includes several characterizing spatial features such as various environmental challenges, including air and water pollution, deforestation, and the depletion of natural resources, land take, socio-economic underdevelopment, potentials in tourism sector etc.

The paper starts to define how ES, integrated with ML techniques, extend the informative potential in spatial explicit classification of a study area. The third section describes the research methodology, input data and computational stages of the analysis.

In the fourth section the results are discussed expressing the high degree of spatial interpretation potential deriving from the regionalization map in terms of statistical similarity of detected regions. Conclusions presents main strengths of the approach and relaunch the need to better define the concept of territorial specialization in ES provisioning in order to reinforce the methodological proposal extending to other relevant case studies.

2 Ecosystem Services: From Multifunctionality to Specialization Perspective

The concept of Ecosystem Services (ES) has gained significant attention in recent years as a means of quantifying the benefits that ecosystems provide to human societies [10, 11]. The framework is based on the idea that nature provides a range of valuable services to people, including clean air and water, nutrient cycling, pollination, and climate regulation, among others. These services are crucial to human well-being and are often taken for granted.

ES provides a robust methodology for evaluating the tradeoffs associated with land-use transformations [12]. As human populations grow and expand into new areas, the need for land use changes increases, often at the expense of natural ecosystems. ES analysis can help decision-makers evaluate the costs and benefits of these changes, taking into account both the direct and indirect impacts on ecosystem services.

Moreover, the ES framework enables the identification of complex dynamics between ecosystems and human societies. By quantifying the benefits of ecosystem services, ES analysis can help stakeholders understand the links between human well-being and natural systems. This can help policymakers to develop more effective policies that balance the needs of society with the long-term health of ecosystems.

One of the key strengths of the ES framework is its ability to facilitate spatially explicit assessments. By mapping the distribution of ecosystem services, stakeholders can identify areas where these services are most valuable and prioritize conservation efforts. This approach can also help to identify areas where development may have the greatest impact on ecosystem services, enabling decision-makers to take a more informed approach to land-use planning [3–5]. Finally, the ES framework promotes communication and joint implementation among stakeholders at different levels of governance.

In particular we refer to ES framework as a powerful tool for decision-making in planning [6]. It enables the evaluation of tradeoffs associated with land-use transformations, identifies complex dynamics between ecosystems and human societies, facilitates spatially explicit assessments. The framework has the potential to promote more sustainable land-use practices that balance the needs of society.

The goal of this work is to learn more from ES assessment through a robust methodology [3, 13–16] that exploits the spatial relevance of ES information. Specifically, the aim is to define a first method for ES specialization analysis using ML regionalization tools [17]. In a general perspective, the results are intended to contribute to land-use planning practices, although many relevant sectorial planning processes may also benefit [18].

The land-use planning system faces structural weaknesses from both regulatory and informative perspectives [19–22]. The lack of flexibility of conventional zoning and prescriptive models applied in urban and regional plans is the first aspect of concern. Recent studies have analyzed the concept of ES multifunctionality as a way to take advantage of the multiple contributions that ES analysis defines in a specific territorial unit (Land Parcel). We refer to the Regulation and Maintenance Ecosystem Services (ReMES), previously computed by Pilogallo and Scorza [12], to consider a relevant stock of ES and scale down analytical tools to a specific study area.

We consider ReMES, defined by the Common International Classification of Ecosystem Services (CICES) [23], as "all the ways in which living organisms can mediate or moderate the ambient environment that affects human health, safety or comfort, together with abiotic equivalents." Although not directly consumed, ReMES has a strong influence on the environment's ability to contribute to the quality of human life.

This paper analyzed in detail the close relationship between ecosystems and human well-being by highlighting the value of pinpointing specialized areas of beneficial delivery in policy and decision-making to land-use planning. In fact, the proposed model aims to explicit the values of environmental conditions and resources that link measures of ecosystem specialization to identified spatial functions in the land. This framework is geared toward measuring the multiplicity of services, functions, and benefits that ES provide in a specific spatial context. Environmental service variety has been widely recognized as a fundamental aspect of ecosystem functioning that can yield a plethora of ecological benefits. A variety set of ES provided habitats and species protection and

improvement, which coincides with biodiversity conservation and enhancement. This is useful because maintaining a functional heterogeneity of the territory ensures the preservation of biodiversity, greater adaptability to climate change, and ensures usability to different beneficiaries [24, 25].

This work develop a preliminary attempt to put in practice the concept of "specialization in ES provision". The perspective is to consider "specialization" not as the prevalence of one ES function over the other, but, rather, is intended to make explicit the complexity that environmental characteristics generating the provision of ES in a specific context (region). Measuring the level of specialization of an area, in comparison with other areas, is a topic widely developed in the ecological field on the bases of broad theoretical framework.

The concept of specialization, in the view of the authors, has to be considered as a geospatial problem generally known as the "Modifiable Areal Unit Problem (MAUP)" and, in these terms, has been faced by the means of robust of statistical analyses. MAUP deals with the choice of spatial units used to aggregate data and through which phenomena are visualized and analyzed [26]. This approach completely suitable to answer key urban studies questions related to the need to reinforce the analytical approaches capacity in managing spatial information complexity. The analysis of geospatial phenomena as well as the definition of regional specialization of ES requires the use of Geographic Information Systems (GIS) techniques, which enable the collection, analysis, and visualization of spatial data. However, the investigation of complex spatial phenomena, such as the search for sub-areas that take into account multidimensional geospatial information, may require the use of more advanced techniques, as traditional GIS methods may no longer be adequate, 'technical debt' [27, 28].

A new paradigm for geospatial technology is already in the pipeline and looks poised to take the stage in the upcoming new geospatial era [29]. Specifically, GeoAI is an interdisciplinary field that draws on a variety of disciplines, including mathematics, computer science and geography that enables the decoding of geographical challenges, with the aid of geospatial Big-data, and without any simplification or loss of valuable information [30, 31]. Wenwen Li illustrates the conceptual three-pillar of GeoAI: geospatial Big-data, computing power and innovation in Artificial Intelligence (AI). Indeed, the increasing availability of large-scale geospatial data can benefit various fields, including all the social sciences, through the use of innovative technologies like GeoAI [32]. By combining the strengths of Geography and AI, researchers can develop comprehensive and effective contribution to decision makers in developing effective strategies for managing spatial phenomena and promoting sustainability [33, 34].

3 Materials and Methods

The paper proposes a data-driven methodology for identifying new geographies of territorial specialization in the provision of ES. This constitutes a contribution to the innovation of spatial analysis techniques for complex phenomena that are fundamental in the context evaluation processes for sustainable planning of land use and transformation decisions. The selected analytical tools are Machine Learning (ML) algorithms, which have proven to be highly effective and statistically robust [35]. The adopted approach

is data-driven, thus, no ex-ante hypotheses have been formulated that simplify the complexity of the analytical dimension [36]. GeoAI allows for the consideration of all the informative complexity of the reference data lake, evaluating the relationships between data. In particular, regionalization is considered as a preliminary phase in the process of defining the concept of specialization for the ES of a particular territorial area.

The base spatial datasets used for the analysis were derived from the material provided and discussed in previous researches [15]. The following ES classes are included in the category of Regulation and Maintenance Services (ReMES) according to the CICES classification:

- Regulation of chemical composition of atmosphere;
- Control of erosion rate;
- Hydrological cycle and water flow regulation;
- Maintaining nursery populations and habitat;
- Pollination.

The methodologies used for evaluating the ES were selected from the suite of InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) models. This is a set of models developed by Stanford University within the "Natural Capital Project" (Natural Capital Project, n.d.), InVEST [37] covers most of the evaluation requirements of the services considered for subsequent analyses. For each of the analyzed ES, corresponding maps were produced for the year 2018. The input database covers the whole Italy, but for the purposes of this research only the territory of the Province of Potenza was considered.

Input dataset refers to the following ES categories:

1. Carbon storage and sequestration (c_stock): This model estimates the amount of carbon (ton/ha) in relation to land use categories, referring to four major natural pools: aboveground biomass, belowground biomass, soil, and dead organic matter.
2. Sediment delivery ratio (SDR): This model calculates the amount of eroded sediment for each pixel and estimates the sediment transport coefficient (SDR) that represents the portion of sediment that actually reaches water bodies. The result is an erosion value per unit area (ton/ha).
3. Nutrient delivery ratio (NDR): This model estimates the surface flow of pollutants (N and P) by calculating a mass balance (nutrient load per pixel) combined with information on land morphology. The result is a nutrient delivery ratio value (kg/ha).
4. Water yield (w_yield): This model estimates the relative contributions of water from different parts of a landscape, providing information on how changes in land use patterns affect annual surface water yield and hydroelectric power production.
5. Crop production (c_prod): This model estimates the average yield (q/ha) of crops (in this case, wheat) and the value of nutrients for a fixed set of crops, derived from user-provided land cover information.
6. Crop pollination (I_abu, I_supp): This model provides an estimate of the abundance of pollinator species per unit area, calculated based on the suitability of the area for nesting and the presence of food.
7. Habitat quality (quality, deg): This model combines information on land use, their ability to support animal and plant species (i.e., biodiversity in a broad sense), and threats to them, resulting in a relative quality map (Habitat Quality) and a degradation

map (Habitat Degradation) of habitats in a range of variation from a minimum (0) to a maximum (1).

The Input data was scaled on the study area boundaries: the territory of the province of Potenza (NUTS2). The main city in the area is Potenza, the regional capital, where most of the population is concentrated and where the main citizenship services are offered. The second largest city in the province, by population, is Melfi, located in the northern part. The rest of the territory has a polycentric settlement structure consisting of small secondary centers and a widespread tendency towards the abandonment of rural settlements by residents in favor of more recently developed areas.

The Provincial Authority, entitled of territorial planning, mapped the Naturalistic Environmental System (SNA) for the Provincial Structural Plan of Potenza in 2013. This analysis highlighted the complex and extensive environmental system of the study area. In particular, there are areas with high naturalness, such as the Vulture area to the north, characterized by geomorphological and naturalistic singularities, already a Regional Reserve of Monticchio. The system runs along the entire Apennine range across three different Parks and ends to the south with the massif of Pollino, the largest protected area in Italy and one of the largest in Europe.

On the bases of the analytic methodology, from each of the national ReMES input maps, SE values were extracted at the provincial level using a regular grid of 178064 points (200 m). The grid works as a control matrix and allowed to develop a database including all statistical characters for each control point identified by the grid.

The dataset was analyzed and corrected for any sampling errors or null values. The subsequent Feature Engineering operations also allowed for the preparation of the dataset for GeoAI algorithms. This process was necessary to improve the performance of ML algorithms.

The Regionalization algorithm (AgglomerativeClustering) was selected in order to account both the statistical variance of characteristics of the spatial relationships in the process of formation of regions [17]. In this regard, the spatial contiguity condition was implemented with the Rook model, applied to a polygonal mesh obtained by applying Voronoi Polygons on the control grid. The Regionalization algorithm is based on a hierarchical agglomerative strategy that takes into account attribute similarity through the linkage criterion (dist) and adds the spatial constraint through the Connectivity matrix (W).

A critical step in the regionalization technique is to define the number (K) of regions that yields a significant result in both statistical and territorial interpretability terms [38, 39]. To identify this critical value, the process was iterated for K values ranging from [10–2000]. The validation process relied on criteria defined in the literature.

Based on this result, the concept of region specialization was explored in-depth. Initially, this concept of specialization was investigated within the dataset using purely statistical approaches. Specifically, the statistical distance between the centroids of each region within the feature space was evaluated as a multidimensional vector using the NearestCentroid algorithm. Finally, analysis of the resulting similarity matrices allowed for mapping the statistical similarity of each region relative to others, which through an empirical comparison approach, enabled identification of regions specialized in providing SE.

4 Results and Discussions

As a result of the whole analytical process, the ES values extracted from the national ReMES maps on the support layer at the provincial (NUTS2) scale represents a valuable dataset also for other applications. It results in a structured database of 178065 features and 9 statistical attributes. Each feature represents a control point of the grid and reflects the associated multidimensional information.

The dataset expresses a multidimensionality of territorial information useful to support subsequent analyses.

The analysis of the literature metrics and the territorial interpretability of the results of the Regionalization algorithm led to indicate K = 200 as the representative number of regions for the study area. The following figure (Fig. 1) shows the map of the 200 regions and the graphs of the criteria adopted in choosing this value.

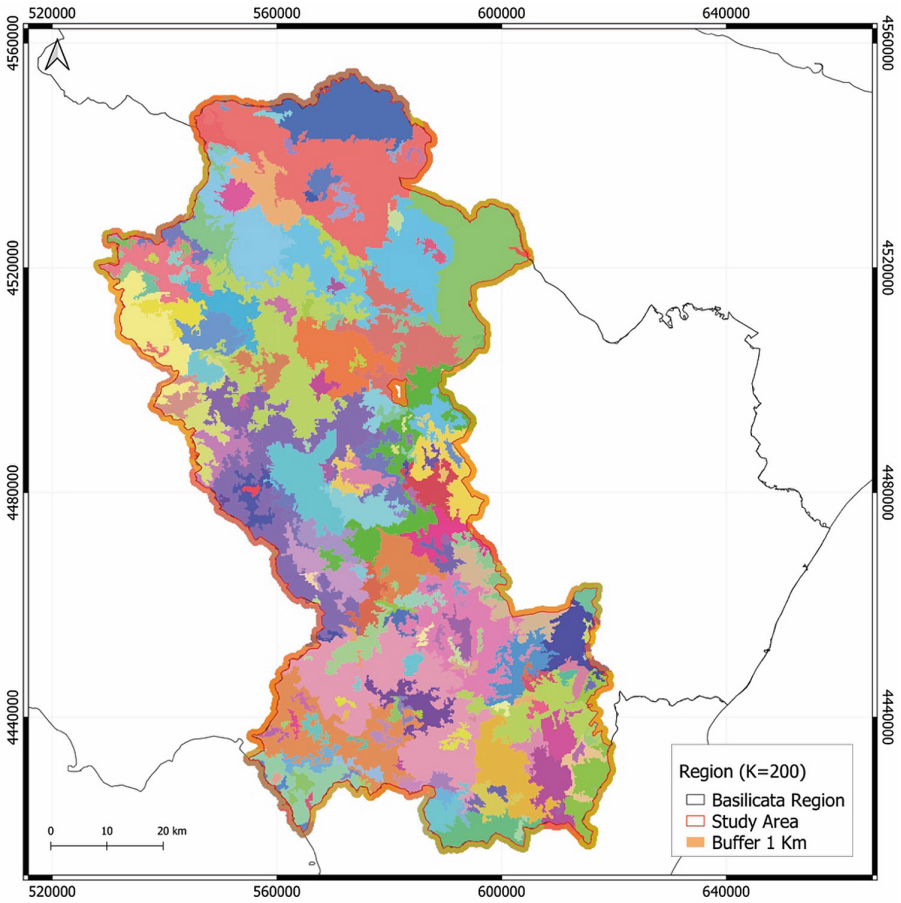

Fig. 1. Regionalization output

The map highlights how the regionalization for K = 200 regions offer a geographically consistent subdivision with the territorial scale of analysis and is particularly useful for evaluating the ES specialization of regions.

Based on this map, the concept of statistical similarity-based specialization of regions was further investigated. The map was classified on a chromatic scale into 5 equal intervals. The lighter tones show the similarity of attributes between regions, while the progressively darker tones highlight strong dissimilarity.

Figure 2 shows the result of this similarity analysis with respect to the region corresponding to the urbanized area of the municipality of Potenza.

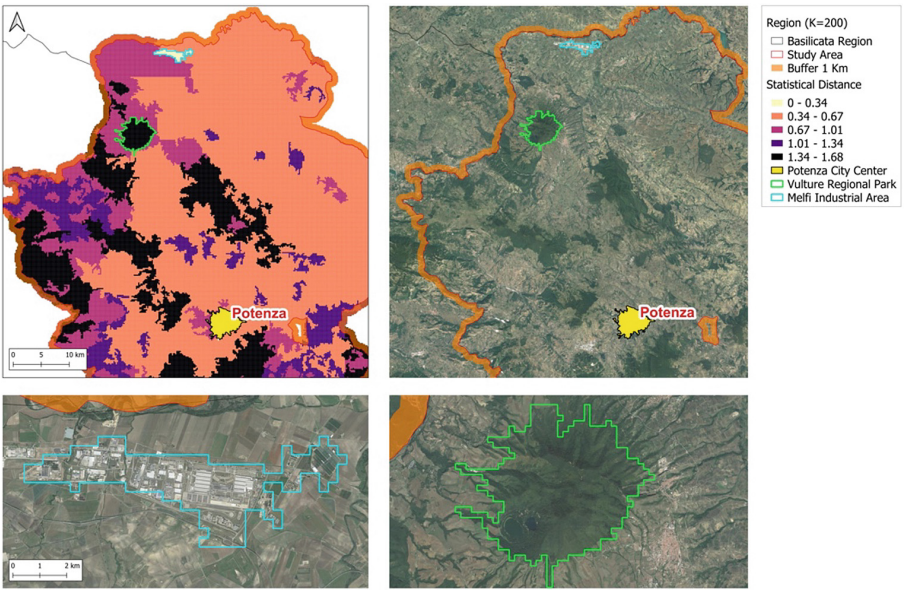

Fig. 2. Statistical similarity-based specialization map of the municipality of Potenza.

Compared to the distribution of the features, this region presents particularly high values of land degradation (deg), while the low values are related to the environmental quality characteristics (quality), the ability to store carbon (c_stock), and the presence and availability of pollinator species in the area (I_abu and I_supp).

This region, recognized as a homogeneous territorial unit in terms of settlement characteristics, shows a peculiar condition compared to the entire study area that makes it strongly dissimilar to those of the provincial territory with a greater naturalistic and environmental vocation. The maximum statistical similarity is evident only with the region that coincides with the industrial complex of Melfi, a heavily urbanized territorial context that shares similar characteristics in terms of environmental quality and degradation.

5 Conclusions

This paper proposes a methodology that integrates spatial evaluations of Ecosystem Services (ES) to define a measure of territorial specialization of ES supply. Such analyses lead to the identification of sub-regions specializing in the provision of specific ES. The concept of specialization, which could be further investigated in relation to research developments, represents a useful decision-making variable to guide territorial governance and management towards more sustainable scenarios.

The analytical procedure, defined to evaluate the spatial distribution of the considered phenomena, is based on the application of robust regionalization algorithms, specific to Machine Learning (ML), trained on a multivariate territorial information dataset. The outputs have been validated through statistical metrics defined in the literature.

The results highlighted the potential of the method, which has allowed the definition of new spatially homogeneous geographies for ES provisioning but also for other complex territorial phenomena [40–45]. The regionalization phase is a preliminary step for identifying specific territorial functionalities in terms of ES provision.

Therefore, the regionalization into homogeneous areas with respect to the characteristics of ES supply integrated with measures of statistical similarity to improve precision and robustness, allowed to overcome the concept of multifunctionality of ES proposed in previous studies.

In conclusion, the analysis of complex spatial phenomena and the identification of potential territorial areas suited for ES provision can offer new interpretations of the territory in the context of the functions and responsibilities [9, 45] that the Province of Potenza influencing multiple sectors: from renewable energy policies [46–48] to tourism development [39, 40, 49–51], from land take to natural capital preservation [5, 52].

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