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Computational Science and Its Applications – ICCSA 2024 Workshops

Hanoi, Vietnam, July 1–4, 2024
Proceedings, Part VII

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Preface

These 11 volumes (LNCS volumes 14815–14825) consist of the peer-reviewed papers from the 55 Workshops of the 2024 International Conference on Computational Science and Its Applications (ICCSA 2024) which took place during July 1–4, 2024 in Hanoi (Vietnam). The peer-reviewed papers of the main conference tracks are published in a separate set consisting of two volumes (LNCS 14813–14814).

The conference was held in a hybrid form, with some participants present in person, hosted in Hanoi, Vietnam, by the Thuy Loi University. We enabled virtual participation 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 2024 was another successful event in the International Conference on Computational Science and Its Applications (ICCSA) conference series, previously held in Athens, Greece (2023), Malaga, Spain (2022), Cagliari, Italy (hybrid with few participants in presence 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 conference 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 2024 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 55 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 Workshops proceedings we accepted 281 full papers, 17 short papers and 2 PhD Showcase papers. In the Main Conference Proceedings we accepted 53 full papers, 6 short papers and 3 PhD Showcase papers from 207 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 2024 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 2024

Osvaldo Gervasi
Beniamino Murgante
Chiara Garau

Welcome Message from Organizers

After the very hard times of COVID, ICCSA continues its successful scientific endeavors in 2024, hosted in Hanoi, Vietnam. This time, ICCSA moved from the Mediterranean Region to Southeast Asia and was held in the metropolitan city of Hanoi, the capital of Vietnam. Hanoi is a vibrant urban environment known for the hospitality of its citizens, its rich history, vibrant culture, and dynamic urban life. Located in the northern part of the country, Hanoi is a bustling metropolis that combines the old with the new, offering a unique blend of ancient traditions and modern development.

ICCSA 2024 took place in a secure environment, allowing for safe and vibrant in-person participation. Combined with the active engagement of the ICCSA 2024 scientific community, this set the stage for highly motivating discussions and interactions regarding the latest developments in computer science and its applications in the real world for improving communities' quality of life.

Thuyloi University, also known as the Water Resources University, is a prominent institution in Hanoi, Vietnam, with a strong reputation in engineering and technical education, particularly in water resources and environmental engineering. In recent years, the University has expanded its academic offerings to include computer science, reflecting the growing importance of technology and digital skills in all sectors. This year, Thuyloi University had the honor of hosting ICCSA 2024. The Local Organizing Committee felt the burden and responsibility of such a demanding task and put all necessary energy into meeting participants' expectations and establishing a friendly, creative, and inspiring scientific and social/cultural environment that allowed for new ideas and perspectives to flourish.

Since all ICCSA participants, whether informatics-oriented or application-driven, realize the tremendous advancements in computer science over the last few decades and the huge potential these advancements offer in coping with the enormous challenges of humanity in a globalized, 'wired,' and highly competitive world, the expectations for ICCSA 2024 were high. The goal was to successfully match computer science progress with communities' aspirations, achieving progress that serves real, place- and people-based needs and paves the way towards a visionary, smart, sustainable, resilient, and inclusive future for both current and future generations.

On behalf of the Local Organizing Committee, I would like to sincerely thank all of you who contributed to ICCSA 2024.

Nguyen Canh Thai

Organization

ICCSA 2024 was organized by Thuyloi University (Vietnam), the University of Perugia (Italy), the University of Basilicata (Italy), Monash University (Australia), Kyushu Sangyo University (Japan), the University of Minho (Portugal), and the University of Cagliari (Italy).

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Sustainable Digital Circular Economy (DiCE 2024)

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Enrico Dagostini	University of Malta, Malta
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Marco Naseddu	University of Cagliari, Italy
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Maria Ronza	University of Naples, Federico II, Italy
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Evaluating Inner Areas Potentials (EIAP 2024)

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Econometrics and Multidimensional Evaluation of Urban Environment (EMEUE 2024)

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Environmental, Social, Governance of Energy Planning (ESGEP 2024)

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Ecosystem Services in Spatial Planning for Resilient Urban and Rural Areas (ESSP 2024)

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Ethical AI Applications for a Human-Centered Cyber Society (EthicAI 2024)

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14th International Workshop on Future Computing System Technologies and Applications (FiSTA 2024)

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Kazuaki Tanaka	Kyushu Institute of Technology, Japan
Toshihiro Uchibayashi	Kyushu University, Japan
Toshihiro Yamauchi	Okayama University, Japan
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Geographical Analysis, Urban Modeling, Spatial Statistics (Geog-An-Mod 2024)

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Andreas Fricke	Hasso-Plattner-Institut für Digital Engineering, Germany
Rodrigo Tapia McClung	Centro de Investigación en Ciencias de Información Geoespacial, Mexico

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Geomatics for Resource Monitoring and Management (GRMM 2024)

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International Workshop on Information and Knowledge in the Internet of Things (IKIT 2024)

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Regenerating Brownfields Enhancing Urban Resilience Appeal (INFERENCE 2024)

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Francesca Moraci	Mediterranea University of Reggio Calabria, Italy
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Celestina Fazia	University of Enna Kore, Italy
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International Workshop on Territorial Planning to Integrate Risk and Urban Ontologies (IWPRO 2024)

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Caterina Pietra	University of Pavia, Italy

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MaaS Solutions for Airports, Cities and Regional Connectivity (MaaS 2024)

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Mara Ladu	University of Cagliari, Italy
Martina Sinatra	University of Cagliari, Italy
Ginevra Balletto	University of Cagliari, Italy

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Marco Mazzarino	IUAV Univeristy Venice, Italy
Maria del Mar Munoz Leonisio	University of Cadiz, Spain
Veronica Camerada	Univeristy of Sassari, Italy

Brunella Brundu	Univerisity of Sassari, Italy
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Enrico Dagostini	University of Malta, Malta
Giovanni Mauro	University of Campania Luigi Vanvitelli, Italy
Maria Ronza	University of Naples, Federico II, Italy
Massimiliano Bencardino	University of Salerno, Italy

Development of Urban Mobility Management and Risk Assessment (MAINTAIN 2024)

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Tiziana Campisi	University of Enna Kore, Italy
Massimo Di Gangi	University of Messina, Italy
Antonio Comi	University of Rome Tor Vergata, Italy
Grigorios Fountas	Aristotle University of Thessaloniki, Greece
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Orlando Belcore	University of Messina, Italy
Marinella Giunta	Mediterranea University of Reggio Calabria, Italy
Borja Alonso	University of Cantabria, Spain
Luigi Dall'Olio	University of Cantabria, Santander, Spain
Kh Md Nahiduzzaman	UBC, Canada

Multidimensional Evolutionary Evaluations for Transformative Approaches (MEETA 2024)

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Ludovica Larocca	University of Naples Federico II, Italy
Maria Somma	University of Naples Federico II, Italy
Gaia Daldanise	National Research Council, Italy

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Caterina Loffredo	University of Naples Federico II, Italy
Giuseppe Ciciriello	University of Naples Federico II, Italy
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Benedetta Grieco	University of Naples Federico II, Italy
Simona Panaro	University of Sussex, UK

Building Multi-dimensional Models for Assessing Complex Environmental Systems (MES 2024)

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Federico Dell'Anna	Politechnic of Turin, Italy
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Models and Indicators for Assessing and Measuring the Urban Settlement Development in the View of Zero Net Land Take by 2050 (MOVEto0 2024)

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Lucia Saganeiti	University of L'Aquila, Italy
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Angela Pilogallo	University of L'Aquila, Italy
Francesco Zullo	University of L'Aquila, Italy
Alessandro Marucci	University of L'Aquila, Italy

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Ilaria Del Ponte	University of Genoa, Italy
Carmen Guida	University of Naples Federico II, Italy
Chiara Di Dato	University of L'Aquila, Italy

4th Workshop on Privacy in the Cloud/Edge/IoT World (PCEIoT 2024)

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Davide Cerotti	University of Piedmont Oriental, Italy

Scientific Computing Infrastructure (SCI 2024)

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Alexander Bogdanov	St. Petersburg State University, Russia
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Downscale Agenda 2030 (SDGscale 2024)

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Maria Attard	University of Malta, Malta
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Maria Ronza	University of Naples, Federico II, Italy
Massimiliano Bencardino	University of Salerno, Italy

Socio-Economic and Environmental Models for Land Use Management (SEMLUM 2024)

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Elena Fregonara	Polytechnic of Turin, Italy
Paola Amoruso	LUM, Italy

Ports of the Future - Smartness and Sustainability (SmartPorts 2024)

Workshop Organizers

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Patrizia Serra	University of Cagliari, Italy
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Marco Petrelli	Roma Tre University, Italy

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Maria Ronza	University of Naples, Federico II, Italy
Massimiliano Bencardino	University of Salerno, Italy

Smart Transport and Logistics - Smart Supply Chains (SmarTransLog 2024)

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Enrico Dagostini	University of Malta, Malta
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Giovanni Longo	University of Trieste, Italy
Luca Toneatti	University of Trieste, Italy
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Massimiliano Bencardino	University of Salerno, Italy

Smart Tourism (SmartTourism 2024)

Workshop Organizers

Silvia Battino	University of Sassari, Italy
Francesca Krasna	University of Trieste, Italy
Maria del Mar Munoz Leonisio	University of Cadiz, Spain

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Veronica Camerada	University of Sassari, Italy
Brunella Brundu	University of Sassari, Italy
Maria Attard	University of Malta, Malta
Tu Anh Trinh	College of Technology and Design for UEH University, Vietnam
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Maria Ronza	University of Naples, Federico II, Italy
Massimiliano Bencardino	University of Salerno, Italy

Sustainable Evolution of Long-Distance Freight Passenger Transport (SOLIDEST 2024)

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Antonio Comi	University of Rome Tor Vergata, Italy
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Luigi Dall'Olio	University of Cantabria, Spain
Antonio Russo	University of Enna Kore, Italy

Sustainability Performance Assessment: Models, Approaches, and Applications Toward Interdisciplinary and Integrated Solutions (SPA 2024)

Workshop Organizers

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ICCSA 2024 took place on the main campus of Thuyloi University in Hanoi, Vietnam.



Plenary Lectures

Harnessing Artificial Intelligence for Enhanced Spatial Analysis of Natural Hazard Assessments



Prof. Dr. Biswajeet Pradhan

Director - Centre for Advanced Modelling and Geospatial Information Systems (CAMGIS), School of Civil and Environmental Engineering, Faculty of Engineering and IT, University of Technology Sydney, Australia

Abstract. In the realm of natural hazard assessments within spatial domains, the advent of Artificial Intelligence (AI) represents a paradigm shift, revolutionizing the way we conceptualize, model, and interpret environmental risks. This keynote address illuminates the profound impact of AI technologies, particularly machine learning algorithms and data-driven approaches, in reshaping our understanding and prediction capabilities concerning natural disasters.

By assimilating and scrutinizing vast spatial datasets, AI-driven models offer unparalleled accuracy and efficiency, facilitating timely and precise hazard assessments. Real-time processing of geospatial information not only enables rapid predictions but also forms the cornerstone of proactive disaster management strategies. Furthermore, AI's capacity lies in its adeptness at deciphering intricate spatial patterns inherent to natural hazards, unraveling subtle cues and previously unnoticed correlations within the data fabric.

This keynote delves into how AI's nuanced interpretation, coupled with advanced algorithms, elevates hazard modeling, providing deeper insights into the spatial dynamics of environmental risks. By augmenting traditional methodologies and revealing hidden patterns, AI fosters comprehensive risk assessments, fostering informed decision-making processes. The fusion of AI and natural hazard assessments in spatial domains heralds a more resilient approach to disaster preparedness and response.

Join us in embracing this transformative era, where AI's sophisticated modeling techniques and precise spatial interpretations converge, heralding proactive and effective mitigation strategies amidst the ever-evolving landscape of environmental challenges.

Short Bio. Distinguished Professor Dr. Biswajeet Pradhan is an internationally established scientist in the field of Geospatial Information Systems (GIS), remote sensing and image processing, complex modelling/geo-computing, machine learning and soft-computing applications, natural hazards and environmental modelling. He is the Director of the Centre for Advanced Modelling and Geospatial Information Systems (CAMGIS) at the Faculty of Engineering and IT at the University of Technology, Sydney (Australia). He was listed as the World's Most Highly Cited Researcher by the Clarivate Analytics Report for five consecutive years, 2016–2020, as one of the world's most influential minds.

He ranked number one (1) in the field of "Geological & Geomatics Engineering" during the calendar year 2021–2023, according to the list published by Stanford University Researchers, USA. This list ranks the world's top 2% most highly cited researchers based on Scopus data. In 2018–2020, he was awarded as World Class Professor by the Ministry of Research, Technology and Higher Education, Indonesia. He is a recipient of the Alexander von Humboldt Research Fellowship from Germany. Between 2015–2021, he served as "Ambassador Scientist" for the Alexander Humboldt Foundation, Germany.

Professor Pradhan has received 58 awards since 2006 in recognition of his excellence in teaching, service and research. Out of his more than 850 articles (Google Scholar citation: 70,000, H-index: 129), more than 750 have been published in science citation index (SCI/SCIE) technical journals. He has authored/co-authored ten books and thirteen book chapters.

Software Engineering Research in a New Situation



Prof. Carl K. Chang

Professor Emeritus, Iowa State University, USA

Abstract. With the rise of Generative Artificial Intelligence (GAI), epitomized by Large Language Models (LLMs), a profound shift has unfolded in software engineering research. In this presentation, I will traverse my four-decade journey in software engineering research, focusing on situational awareness in the era of the Internet of Things (IoT). I have witnessed the turbulence brought forth by the AI community that demands changes in our approaches. Meanwhile, owing to the pervasiveness of services computing, services became the first-class citizen in modern-day software engineering methodologies.

I argue that situational awareness must permeate the entire lifecycle to consistently deliver software services that align with the dynamic needs of users and the ever-evolving environments. I will elucidate this argument by reviewing the Situ framework, offering a comprehensive illustration of my perspective. Furthermore, I will outline my vision regarding the formidable research challenges considering the rapidly shifting landscape dominated by an irresistible and profoundly disruptive generative AI tsunami.

Short Bio. Carl K. Chang is a former department chair and Professor Emeritus of Computer Science at Iowa State University. His research interests include requirements engineering, net-centric computing, situational software engineering and digital health. Chang was the 2004 President of the IEEE Computer Society. Previously he served as the Editor-in-Chief for IEEE Software (1991–1994), and as the Editor-in-Chief of IEEE Computer (2007–2010). He was the 2012 recipient of the Richard E. Merwin Medal from the IEEE Computer Society. Chang is a Life Fellow of IEEE, a Fellow of AAAS, and a Life Member of the European Academy of Sciences (EurASc).

Interpretability and Privacy Preservation in Large Language Models (LLMs)



Prof. My Thai

University of Florida (UF) Research Foundation Professor
Associate Director of UF Nelms Institute for the Connected World

Abstract. Large Language Models (LLMs) have transformed the AI landscape, captivating researchers and practitioners with their remarkable ability to generate human-like text and perform complex tasks. However, this transformative power comes with a set of critical challenges, particularly in the realms of interpretability and privacy preservation. In this keynote, we embark on an exploration of these pressing issues, shedding light on how LLMs operate, their limitations, and the strategies we can employ to mitigate risks. We begin by examining the interpretability in LLMs, which often function as enigmatic "black boxes." Their complex neural architectures make it challenging to understand how they arrive at specific outputs. This lack of transparency raises questions of trust and accountability. When deploying LLMs in real-world applications—whether for chatbots, content generation, or decision-making—it becomes crucial to demystify their decision paths.

We will use explainable AI (XAI) to offer faithful explanations, from the black-box to white-box models, and from feature-based [1, 2] to neuron circuits-based [3, 4] explanations. By visualizing attention mechanisms, feature importance, and saliency maps, we empower users to comprehend LLM predictions. XAI not only fosters trust but also encourages responsible utilization of LLMs.

We next turn our attention to one of the utmost concerns and challenges: data privacy. LLMs process vast amounts of data, raising risks of data leakage, model inversion, the right to be forgotten, and inadvertent exposure of sensitive information. Furthermore, the integration of LLMs into diverse applications also significantly brings these challenges to the next level [5]. This talk explores strategies to protect privacy, including differential privacy, federated learning, and data encryption.

Short Bio. My T. Thai is a University of Florida (UF) Research Foundation Professor, Associate Director of UF Nelms Institute for the Connected World, and a Fellow of IEEE and AAIA. Dr. Thai is a leading authority who has done transformative research in Trustworthy AI and Optimization, especially for complex systems with applications to healthcare, social media, critical networking infrastructure, and cybersecurity. The results of her work have led to 7 books and 350+ publications in highly ranked international journals and conferences, including several best paper awards from the IEEE, ACM, and AAAI.

In responding to a world-wide call for responsible and safe AI, Dr. Thai is a pioneer in designing deep explanations for black-box ML models, while defending against explanation-guided attacks, evident by her Distinguished Papers Award at the Association for the Advancement of Artificial Intelligence (AAAI) conference in 2023. At the same year, she was also awarded an ACM Web Science Trust Test-of-Time award, for her landmark work on combating misinformation in social media. In 2022, she received an IEEE Big Data Security Women of Achievement Award. In 2009, she was awarded the Young Investigator (YIP) from the Defense Threat Reduction Agency (DTRA), and in 2010 she won the NSF CAREER Award. She is presently the Editor-in-Chief of the Springer Journal of Combinatorial Optimization and the IET Blockchain Journal, and editor of the Springer book series Optimization and Its Applications.

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Contents – Part VII

The Development of Urban Mobility Management and Risk Assessment (MAINTAIN 2024)

A Mesoscopic Approach for Calculating Resilience Indicators in Emergency Conditions 3
Massimo Di Gangi, Antonio Polimeni, and Orlando M. Belcore

Analysis of Injury Severities of Accidents Involving Low-Emission Vehicles 16
Ersaia Akritidou, Andromachi Ioannidou, Grigorios Fountas, and Socrates Basbas

Planned and Implemented Actions by Exercises 28
Francesco Russo and Corrado Rindone

The Study of the 5-min Walking Accessibility for Pickup Points in Thessaloniki: Enhancing Logistics' Last Mile Sustainability 41
Antonio Russo, Socrates Basbas, Efstathios Bouhouras, Giovanni Tesoriere, and Tiziana Campisi

Investigating Commercial Vehicles' Parking Habits in Urban Areas: The Case of Thessaloniki, Greece 54
Efstathios Bouhouras, Anastasia Koenta, Vasileios Giannoudis, Socrates Basbas, and Tiziana Campisi

Analysis of e-scooter Users' Riding Behaviour at Signalized Junctions 65
Andreas Nikiforiadis, Pantelis Chatzimatos, Christos Grivas, Ioannis Gryllias, Alexios Toutzaris, Nikiforos Stamatiadis, George Botzoris, and Socrates Basbas

Impact of COVID-19 on Urban Mobility: Empirical Evidence and Lesson Learnt 79
Antonio Comi and Antonio Polimeni

Urban Freight Transport and Emerging Information and Communication Technologies: Analysing End-Consumers Decision in Receiving E-purchases 97
Antonio Comi and Olesia Hriekova

Willingness to Subscribe to a Meal Kit Delivery Service: A First Investigation on Its Generated Impact in Italy 114
Lupini Pagliara Luca, Nigro Marialisa, and Stimilli Arianna

Experimentation on Risk Reduction by Training: A Framework for Seminar Activity 129
Corrado Rindone and Marialuisa Moschella

Building Multi-dimensional Models for Assessing Complex Environmental Systems (MES 2024)

Supporting the Planning Management of UNESCO Sites: A Literature Review Between Urban Showcase and Gentrification 147
Vanessa Assumma, Sebastiano Barbieri, Marta Bottero, and Caterina Caprioli

Geo-NLP Insights: Unveiling Residential Real Estate Trends Through Textual Analysis 163
Marta Bottero, Federico Dell'Anna, Sara Monaci, and Simone Persico

Innovating Urban Systems Through Nature-Based Solution for a Circular Economy Enhancement: A General Framework 176
Alessandra Oppio, Giulia Datola, Tuna Oksuz, Damla Ozgur, and Leopoldo Sdino

Evaluation of Land Use and Environmental Comfort in Reinventing Cities Competition: The Case of La Folie, Bobigny, France 189
Gabriele Paganelli, Camilla Misani, Letizia Soffiantini, Gabriele Masera, Francesco Pittau, and Giorgia Sugoni

Renewable Energy Communities: An Urban Capability-Based Approach to Evaluate Differential Participation in Cities 207
Becchio Cristina, Bottaccioli Lorenzo, Bottero Marta, Cavana Giulio, Fancello Giovanna, and Sciullo Alessandro

Enhancing High-Speed Train Line Design: The Role of Multidimensional Assessment Tools 225
Alessandra Oppio and Marta Dell'Ovo

MaaS Solutions for Airports, Cities and Regional Connectivity (MaaS 2024)

Application of Geospatial Analysis to Tourist Flows in the Insular Destinations 241
Ginevra Balletto, Mara Ladu, Martina Sinatra, and Giuseppe Borruso

The Challenges of Demographic Transition. Network Analysis to Assess Spatial Accessibility to the Emergency Health System 253
Mara Ladu and Ginevra Balletto

A Scoping Review of the Barriers and Prerequisites for MaaS Implementation in Low-Demand Contexts 265
Sara Faedda, Tanja Congiu, Alessandro Plaisant, and Chiara Garau

Beyond Cost-Benefit Analysis. A Methodological Approach to Access Transport Infrastructure Investments 283
Ginevra Balletto, Giuseppe Borruso, Marco Naseddu, Martina Sinatra, and Gianfranco Fancello

Regional Disparity, Accessibility, and Sustainable Mobility in Insular Contexts 294
Mara Ladu, Ginevra Balletto, Tanja Congiu, and Gianfranco Fancello

Downscale Agenda 2030 (SDGscale 2024)

The Role of Spatial Proximity and Urban Functions Density in the Sports Mega Events 309
Martina Sinatra, Ginevra Balletto, Giuseppe Borruso, and Francesco Sechi

Critical Interpretation of SDGs Strategies at Regional Scale: Are There More Important Goals for Italy? 325
Anna Richiedei, Michele Pezzagno, and Ginevra Balletto

Scientific Computing Infrastructure (SCI 2024)

Graph Neural Networks for Metrics Prediction in Microservice Architecture . . . 343
Anna Golovkina, Dmitry Mogilnikov, and Vladimir Ruzhnikov

A Promising Approach to Detect Early Signs of Disease in Old Age 358
A. Bogdanov, N. Shchegoleva, and N. Zalutskaya

Analysis of Attacks on Continuous Authentication Methods and Ways of Defending Against Them 369
Iurii Matiushin, Vladimir Korkhov, and Ilya Busko

Analysis of Privacy Leakage Risks in the Context of Security Threats Associated with Digital Device Fingerprinting 386
Ivan Podsevalov, Alexei Podsevalov, and Vladimir Korkhov

A New Approach to Managing Smart Environment Infrastructure Settings 405
Gennady Dik, Alexander Bogdanov, Nadezhda Shchegoleva, Aleksandr Dik, and Jasur Kiyamov

Author Index 421

The Development of Urban Mobility Management and Risk Assessment (MAINTAIN 2024)

A Mesoscopic Approach for Calculating Resilience Indicators in Emergency Conditions

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Abstract. A transport system involved in a hazardous event may experience some changes in demand (the users want to move all together) and in supply (disruption). By considering these elements, this work aims to provide a measure of the resilience of a road network when a sudden event occurs, focusing on the use of some indicators for resilience evaluation to support an emergency plan. The approach considers both the outgoing flow from the study area and the incoming one (e.g., rescue vehicles). An aspect that will be evaluated concerns the variation in resilience over time. In fact, for events whose effects are not immediate or are distributed over a period of time, resilience may change because the magnitude of the effects on the network changes. A simulation of the transport system, based on a mesoscopic approach, allows one to calculate the indicators for each time interval.

Keywords: resilience · road network · dynamic assignment · assessment · indicators · planning

1 Introduction

Resilience of a system can be defined as its ability to return to its initial state after having undergone an event (natural or anthropic) that perturbed such a state. In a transport system, a sudden event, or an event whose effects spread over time, can cause disruptions in the road network, with impacts on how users move within the area (for example, because of reduction of the available routes). The impossibility of using some arcs in a road network due to damage or other obstacles that can arise in an emergency reduces the performance of the network in terms of travel times [1, 2]. The importance of resilience is even more evident in the situations where the event results in evacuation of the area considered ([3–7]). In this case, there are both people trying to leave the area to go to a safe place and rescue operators entering the area to provide help.

Thus, the problem arises of strengthening the transport network to minimize loss of performance. This can be achieved, for example, if there are alternative (redundancy) routes that allow one to bypass unusable arcs. This type of analysis provides information on the resilience of the transportation network and possible methods to quantify it.

Studies on road network provide information on the ability of the system to withstand extreme events and its ability to return to initial conditions. The resilience assessment

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passes through the evaluation of other network indicators, such as travel time reliability ([8, 9]), capacity ([10, 11]), vulnerability ([12, 13]).

Considering a sudden event, its effects will influence the system for a certain period of time during which resilience will first have a decrease and then a variation (growth or decrease) in relation to what happens within the system. However, if the event is not sudden [14], its effects spread throughout the system over a certain period of time, during which the performance continues to decrease. The recovery phase then follows with a gradual return to the initial value. The approach proposed in this paper allows us to evaluate the system performance indicators in both cases.

Figure 1 shows a general situation. An event occurs at instant *t1,* and the network performance decreases immediately. The duration of the event is up to instant t_2, where its effects end, causing a further decrease in performance due to congestion effects caused by the users moving in the network. Restoration operations could begin at instant t_3 with a consequent increase in performance (from t_2 and t_3 the performances could continue to decrease because network travel costs have increased). It is possible to note that, in the particular case of an evacuation, the start of the evacuation can be any instant after t_1. From the previous considerations, it emerges that two factors must be considered: the disruptions due to the event and the effects due to the peak demand using the road network.

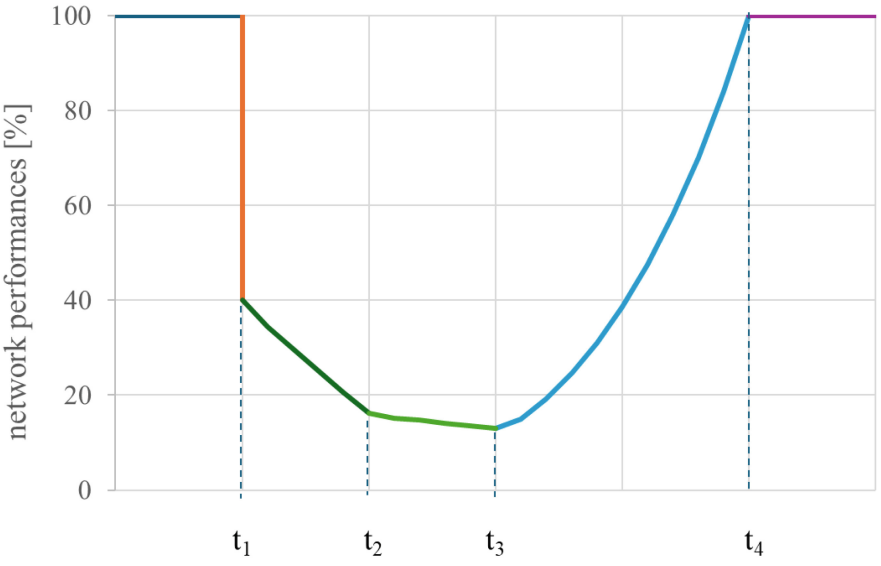

Fig. 1. Performance and resilience.

This work, taking into account that road network performance (and consequently resilience) depends on time, proposes an approach based on dynamic assignment (a mesoscopic approach) able to assess the network over time (the approach is based on

discrete time intervals). The indicator used in this (preliminary) approach is based on the variation in the available routes and in their cost.

The paper is structured as follows. Section 2 contains a review of the literature, Sect. 3 summarizes the proposed methodology, and Sect. 4 reports on a test application. Finally, the conclusions and future developments.

2 Literature Review

The impacts of hazardous events cause disruptions to the road network, which affect resilience. Several works in the literature tackled this topic from different points of view. Without the presumption of exhaustiveness, we will follow a brief review on this topic.

Ilbeigi [15] introduced a statistical approach to evaluate resilience in relation to the duration of the disturbance caused by the event and the variation in the performance of the network before and after the event. Ganin et al. [16] estimated the resilience of a road network by considering the effects resulting from road disruption. In this approach, the resilience has been evaluated for different degrees of arc disruption, using as an indicator the total user delay. Hsieh and Feng [17] examined the resilience of an highway network, highlighting the factors that can be used in modeling resilience. Edrissi et al. [18] linked resilience to the concept of network reliability. Classifying arcs in relation to their contribution to network resilience, the importance of an arc is derived from the probability of failure. In this way, the operations needed to improve the network start with the most important arcs. Similarly, Martin et al. [19] developed a framework capable of assessing resilience in relation to accessibility, also considering the cumulative effects on the arcs of different events. Qiang and Xu [20] proposed measuring the resilience of a road network in relation to the variation of accessibility during a disruption event. Gauthier et al. [21] quantified the resilience of the network by considering as a measure the variation in travel costs. Identified the arcs most critical for the operation of the road network, a procedure is proposed to assess the impact of disruptions on the network and the ability of the network to return to its initial state. Li et al. [1] proposed a framework for assessing resilience when a chain of disruptive events occurs, taking into account that repair actions may not be concluded between one event and the next. This approach can be used for long-term planning in order to define measures for resilience improvement. Similarly, Aydin et al. [22] proposed a multistep approach to plan recovery procedures after network disruption and compared the time to return to normality in relation to the recovery strategies adopted. Zhang et al. ([23]) presented an approach to assess the resilience of the road network based on the fundamental diagram ([24]) inserted within a dynamic model, the purpose being to simulate the trend of traffic congestion in relation to speed. Faturechi and Miller-Hooks [25] developed a bilevel approach to evaluate and optimize the reliability of a road network (in terms of travel time) when a disruptive event occurs. In the resilience evaluation, the behavior of users is considered.

Kaviani et al. ([26]) proposed a model to optimize the locations of roadside information systems with the aim of reducing total travel time in a disrupted network. Ma et al. [27] developed a framework to assess the resilience of a road network when rainwater accumulates on roads and affects speed. Similarly, Chalkiadakis et al. [28] proposed a framework for evaluating the resilience of a road network under the assumption of

failure of some elements, while Akbarzadeh et al. [29] evaluated the effect that the failure of a node or arc has on the entire network, linking this aspect with the definition of resilience. Aghababaei et al. [30] proposed a resilience measure that evaluates the impact of not available trips and the increased travel time in a post-disaster situation. This indicator, evaluated over time, also takes road network recovery actions. Wu and Chen [31] developed a methodology for the assessment of road resilience taking into account the counter-flow operations needed in the affected area to provide assistance to people. The aim of the approach is to increase the availability of routes (redundancy) to facilitate access to emergency vehicles.

3 Methodology

It is useful to remember that when an event causes an emergence condition, the decline in network performance (and therefore its return to initial conditions) depends not only on disruptions caused by the event but also on the fact that the users move on the network despite the impediments.

The approach described in this section (Fig. 2) aims to calculate some network and resilience indicators based on dynamic simulation of road transport dynamic simulation. The dynamic approach allows these indicators to be evaluated for each time interval, allowing us to evaluate how resilience varies over time. The simulation of the system is carried out using a mesoscopic approach [32], considering a set of discrete time intervals.

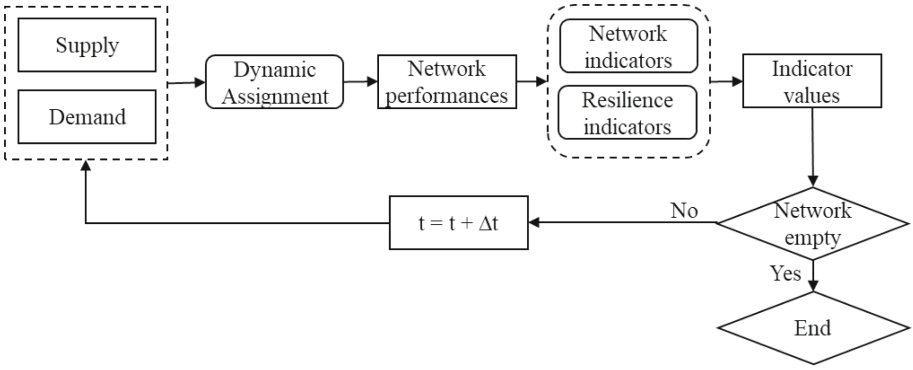

Fig. 2. The proposed procedure.

The procedure takes as input the *supply* and *demand*; both depend on the discrete time interval t considered. The supply is represented by a graph $G\ (N, L)$, where N is the set of nodes and L is the set of arcs. Each arc is supposed to consist of two parts: a running segment and a queueing segment; the separation point S between them is influenced by the flow conditions and its position is calculated at the beginning of each simulation interval. Other elements considered in the width of the simulation are the arc (C_a), the capacity (Q_a, assumed as the capacity of the final section of the arc), and a threshold value for the density of the arc ($k_a{}^{max}$). In this approach, vehicles moving on the network

are grouped into homogeneous packets, each of which is characterized by a departure instant η, an origin-destination pair *rs,* and a vehicle class u (each vehicle class has some characteristics, such as speed and occupancy, associated with it). Thus, considering a packet $p\{\eta, rs, u\}$ such a packet contains vehicles of the same class u that travel from r to s starting in the same instant η. The outflow conditions are supposed to be homogeneous for each arc and do not vary within a time interval. The output of the assignment is the *network performances* (for each interval) in terms of link flows and travel costs. From this output, some *indicators* (both for the *network* and for *resilience*) are considered. In normal situations, it may happen that the user adapts the route choice while moving from the origin to the destination (re-routing). Even in emergency situations, such an eventuality can be hypothesized. In both cases, the available routes depend on the user's location on the network. Without harming the generality of the approach, it is assumed that the user evaluates the available routes at the beginning of each simulation interval. Let be: x the position of the generic user (such a position coincides with the origin at the beginning of the first interval), I_{xs} the set of routes from current position to destination s, the first *resilience indicator* is defined as follows:

$$R_k = \frac{\sum_x \sum_s \sum_{k \in I_{xs}} \gamma^B_{xsk} \cdot g^B_k}{\sum_x \sum_s \sum_{h \in I_{xs}} \gamma^A_{xsh} \cdot g^A_h} \tag{1}$$

A transformation of the indicator reported in Eq. (1), to which a behavioral interpretation can be given [33], can be the following:

$$R_a = \frac{\ln \sum_k \exp(-g^B_k)}{\ln \sum_h \exp(-g^A_h)} \tag{2}$$

Equation 1 considers as the resilience metric the variation of the available routes before (superscript B) and after (superscript A) the event. γ^B_{xsk} is a binary variable equal to 1 if the route k connects the current position x of the user with the destination s, 0 otherwise; ${g^B}_k$ is the cost of the route from the current position of the user to the destination. Equation 2 deals with the variation in satisfaction of the users (can also be seen as a variation in accessibility), expressed the ratio between the logsum [33] of systematic utility V of the available routes before and after the event. Obviously, the value of both indicators is equal to 1 if, in a specific time interval, the system does not change.

Another indicator considered ([12]) is related to each packet moving on the network, and can be considered as the weakness of the network. Let:

$$n^K_{xs} = \sum_{k \in I_{xs}} \sum_{l \in L} \delta_{lk} \tag{3}$$

$$\xi^l_{xs} = \sum_{k \in I_{xs}} \delta_{lk} \quad \forall l \in L \tag{4}$$

$$\zeta_l^{xs} = \begin{cases} \xi_{xs}^l & if\ \xi_{xs}^l = 1 \\ 1 & if\ \xi_{xs}^l > 1 \\ 0 & otherwise \end{cases} \tag{5}$$

$$n_{xs}^G = \sum_{l \in L} \zeta_l^{xs} \tag{6}$$

where x is the current position of the generic packet, δ_{lk} is the generic element of the arcs-routes incidence matrix (equal to 1 if the arc l belongs to the route k, 0 otherwise) and I_{xs} is the set of routes for the origin-destination pair xs (*choice set*).

Following the previous definitions, the index is formalized as follows:

$$R_w^{xs} = \begin{cases} \dfrac{\frac{n_{xs}^K}{n_{xs}^G} - 1}{|I_{xs}| - 1} & if\ |I_{xs}| > 1 \\ 1 & if\ |I_{xs}| = 1 \end{cases} \tag{7}$$

In Eq. (7) the resilience indicator relies with routes and their topology for each origin-destination pair. In fact, the element n_{xs}^K is the count of the arcs belonging to the routes in the choice set (without considering overlaps), while the element n_{xs}^G is also a count of arcs, but counting the arcs common to different routes only once. The value of this indicator is in the interval [0, 1]: a value of 0 indicates that for the xs pair there is more than one route and that there is no overlap between the routes, while a value of 1 indicates the availability of just one route for the xs pair. Note that, since the number of routes depends on the position of the user, the size of the choice set may vary during simulation.

Regarding network indicators, a first indicator is the network clearance time, defined as the difference between the time the last packet p reaches the destination and the beginning of the simulation τ.

$$T_C = \max_{i,r,s} \left[\eta_s^i - \tau \right] \quad i \in P \tag{8}$$

where P is the set of packets.

Let T_s be a threshold value for the clearance time and P_s ($P_s \subseteq P$) the set of packets arriving at the destination in a time less than T_s, defined as:

$$P_s = \left\{ i \in P | (\eta_s^i - \tau) \leq T_s \right\} \tag{9}$$

The second indicator considered is the rate at which packets arrive at their destination before T_s:

$$S = |P_s|/|P| \tag{10}$$

4 Application

An application is provided to test the effectiveness of the proposed approach. The site test chosen for the application is the city of Avellino, located in the Campania region, South Italy (Fig. 3). The city ([34]) covers an area of approximately 2.8 square kilometers and has approximately 420.000 inhabitants. For the objectives of this work, the central part of the city (Fig. 4, approximately 55.000 inhabitants) was considered. The road network is represented by a graph (Fig. 4) consisting of 112 nodes and 283 arcs. Each arc is characterized by length, width, number of lanes, free flow speed, and capacity.

For the purposes of this test, an emergency scenario is generated by assuming that the river crossing the city overflows its banks and partially floods some streets, affecting the capacity and speed with related reduction in the network performance (this scenario is one of those hypothesized by the Italian civil protection in relation to the emergency plans made for the city). The arcs involved in the event are eleven, and for these arcs the speed is reduced by 75%, the capacity is reduced by 90%.

The simulation is done for discrete intervals, each of which has a width of 10 min, and the demand is generated for the first 6 intervals. The event occurs in the interval $h = 2$: it is assumed that the effect is immediate on the arcs.

Figure 5 shows a comparison between the total travel time in the current scenario and the travel time in the emergency scenario. To make the figure clearer, couples for which the travel time increased by more than 20% were considered. In this application, there are about 27% of simulation intervals where the travel time remains the same, about the 12% where the increase in travel time is less than 5%, and the 10% for whom the time more than doubled (Fig. 6).

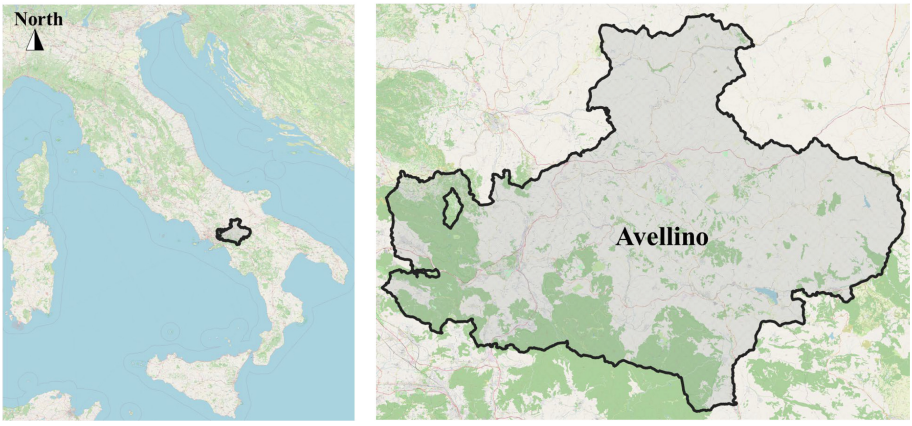

Fig. 3. Avellino test area (background map from OpenStreetMap, [35]).

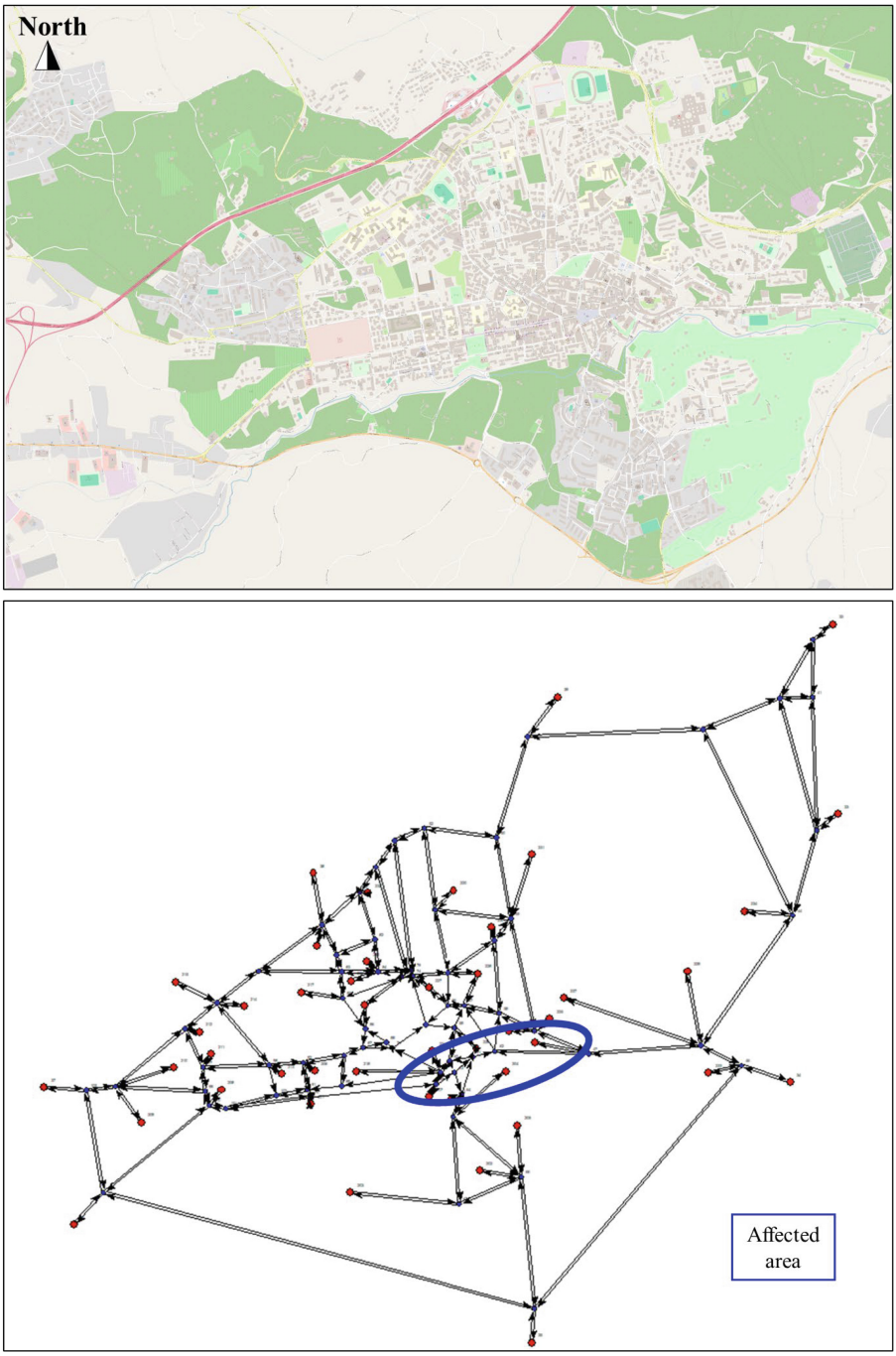

Fig. 4. The central area of the city and the related graph (background map from OpenStreetMap, [35]).

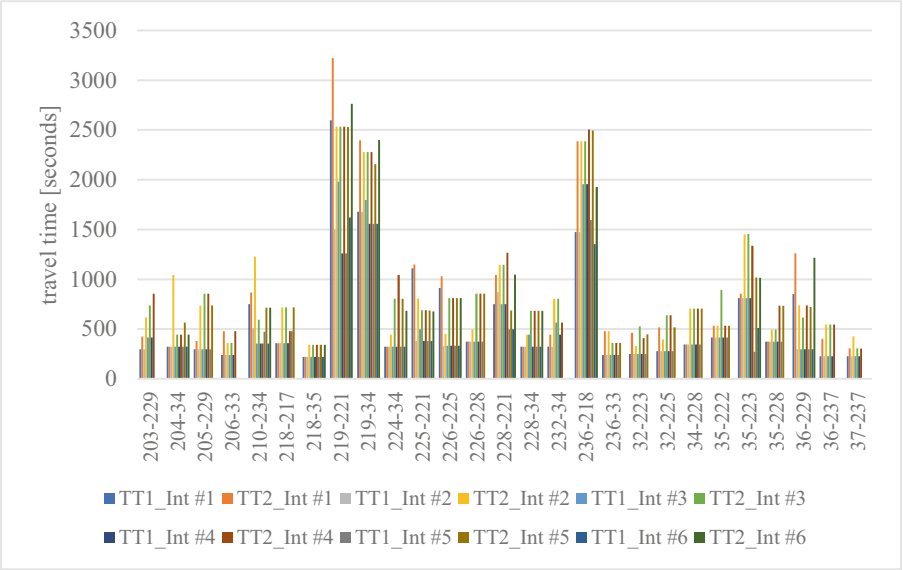

Fig. 5. Comparing the travel time: current scenario *vs* emergency scenario.

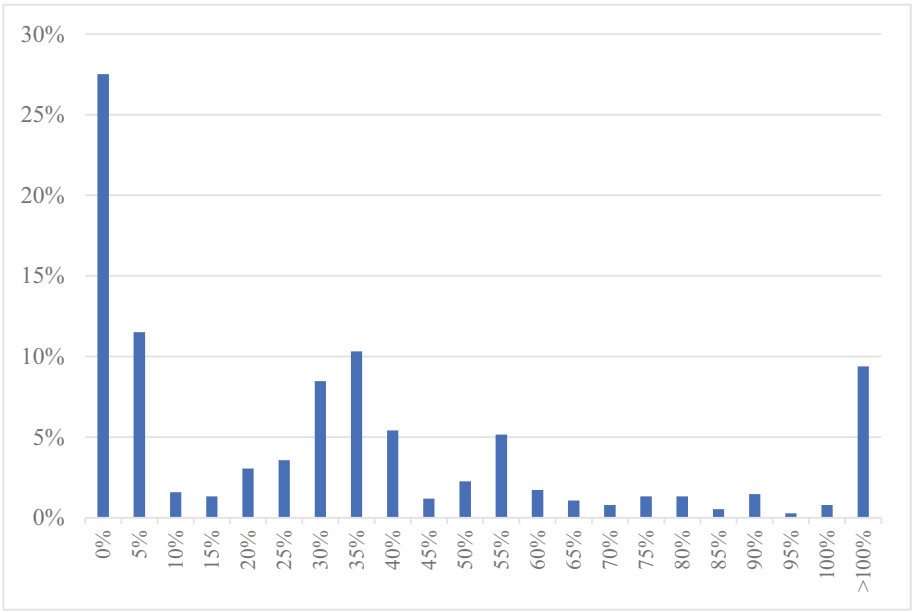

Fig. 6. Frequency analysis of travel time variation.

Figure 7 shows the trend of the resilience indicator for some o-d pairs per time interval. For definition, such and indicator decrease increasing the travel time. For some o-d pairs in Fig. 7 the indicator decreases as expected, but for other increases in the first interval. This can be explained considering that there are users who, due to the disruption, have to change their route and do not load the arcs belonging to the route of another o-d pair.

In relation to the other indicators, the weakness has no appreciable changes (less than 1%). The network clearance time is of 112 min in current scenario and of 222 min in the emergency scenario. Assuming the clearance time of the network in the current scenario as the reference time, the rate of packets that reach the destination in such a time during emergency is equal to the 74.9%.

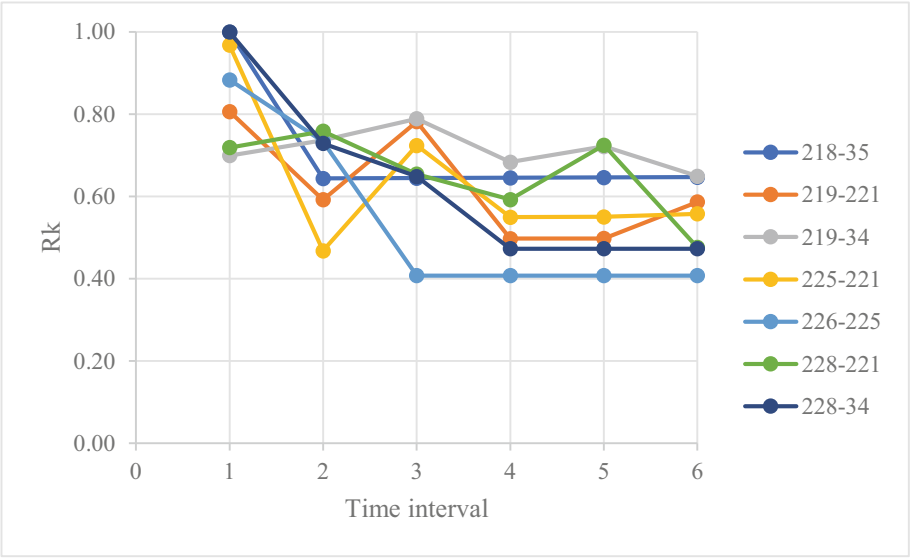

Fig. 7. Resilience indicator per o-d pair.

5 Conclusion

The response of a road network when a sudden event causes an emergency is essential to guarantee the reliability of the travel time of users. To do this, it is possible to evaluate the resilience of the network using appropriate indicators. In this paper, two resilience indicators have been proposed. A first indicator compares the variation of the available routes before and after the event (this value can also be interpreted as the variation of the satisfaction of the users). A second indicator is still on routes, but it is topological and compares the alternative routes in terms of arcs. Besides, two additional performance indicators are defined; they are related with the clearance time and the rate of users arriving at the destination before a reference time. These indicators have been used to evaluate the performance of a real network when an event occurs and produces disruptions.

As a case test, an emergency scenario has been defined in a real city (Avellino, south Italy) where the overflowing of a small river has been hypothesized. Two mesoscopic simulations have been performed, performed on the test network, to evaluate the performance in the current scenario and in the emergency scenario.

Future developments are based on the definition of more resilience indicators and with a large-scale application, also considering the overlapping effects of different events.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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Analysis of Injury Severities of Accidents Involving Low-Emission Vehicles

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Abstract. In recent years, there has been a significant increase in the use of electric and hybrid vehicles on roads worldwide, as governments and road users seek to reduce emissions and promote sustainable transportation. However, as the number of these low-emission vehicles on the roads continues to grow, so does the concern about how safe they truly are. Although electric and hybrid vehicles have been shown to produce lower rates of accidents than vehicles with conventional fuel combustion engines, there is limited evidence as to the factors that may affect the severity of crashes involving low-emission vehicles.

This research is conducted using evidence from crashes involving electric and hybrid vehicles in the United Kingdom. The study uses data from the STATS19 dataset to identify common patterns and trends underpinning the injury severity of occupants and other road users involved in crashes with electric and hybrid vehicles. Through inferential statistical tests and models, this analysis controls for factors, such as the accident location, road and driver characteristics, with a goal to identify the key factors contributing to the occurrence of accidents and quantify their impact on the severity of sustained injuries. Among others, the road speed limit, the road type, as well as weather conditions were identified to affect the likelihood of severe injury outcomes. The findings of this study can assist policymakers and local Authorities in designing and implementing appropriate mobility management systems targeted at the users of low-emission vehicles to enhance road safety and mitigate collision risk.

Keywords: electric vehicles · hybrid vehicles · accidents · injury severity · ordered regression

1 Introduction

According to the "Global Status Report on Road Safety 2023" published by the World Health Organization (WHO), almost 1.2 million lives are lost annually across the globe as a result of road rashes. Between 20 and 50 million people are involved in non-fatal crashes, with many victims facing some form of disability or permanent health problems, potentially significantly affecting their quality of life in the long term (Global status report on road safety, 2023). As such, road safety constitutes a major public health issue, which

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requires the implementation of effective interventions to eliminate the effects of road crashes on societies and economies.

The emergence and broad use of low-emission vehicles, and especially, electric and hybrid-electric vehicles may cause shifts in the determinants of road crashes, and consequently, on the countermeasures that need to be applied. Interestingly, by 2030, it is expected that 56% of vehicles will run on internal combustion engines, while 35% of the fleet will consist of hybrid vehicles and 9% will be electric. The corresponding percentages recorded in 2013 were 98% for gasoline or diesel vehicles, while hybrid and electric vehicles accounted for only 2%. The target for uptake of electrification signifies a complete transition to electric and hybrid vehicles, which are expected to comprise 100% of the fleet in circulation within 15–20 years (Telang et al., 2021). While the share of low emission vehicles into the automotive market is constantly growing, concerted efforts have been directed towards scrutinizing the safety ramifications of road accidents involving these emerging vehicle types.

At the core of robust decision-making frameworks in road safety is the need for a thorough investigation into the implications of electric and hybrid vehicles being involved in road accidents. Prior to the implementation of safety countermeasures and the delineation of pertinent strategies, a comprehensive understanding of the evolving landscape engendered by these novel vehicle technologies is essential. This underscores the necessity for an exhaustive appraisal of the safety landscape vis-à-vis the proliferation of electric and hybrid vehicles. Such an appraisal is critical for ensuring the efficacy and integrity of subsequent road safety interventions to national or international policies.

The key road safety issues stemming from the electric and hybrid-electric vehicles are associated with several operational and design factors. The use of lithium-ion batteries, which is quite frequent in EVs, may pose risks such as thermal runaway, fire, and explosion, especially following incidents of overcharging or crashes with other vehicles (Huang et al., 2021). The charging infrastructure of electric vehicles may serve as an additional source of accidents or safety incidents. Inadequate or poorly designed charging infrastructure can contribute to accidents, especially if charging cables induce safety hazards (Guzek et al., 2024) or other charging incidents that may result in more serious events, potentially fatal, such as overcharging, ignition, leaks, etc. (Wang et al., 2019).

Potential road safety issues may also emerge from the low-noise operation of electric and hybrid-electric vehicles. Electric and hybrid vehicles exhibit a distinctive feature - their almost silent operation, especially noticeable at speeds below 20-30 km/h despite emitting low-frequency sounds. This characteristic becomes even more pronounced in vehicles powered solely by electric energy, where the sound is 1-3 dB weaker compared to hybrids. As speed increases beyond 50 km/h, the friction sound generated by the tires on the road nullifies any difference in sound levels. This seemingly innocuous feature harbors potential risks for vulnerable road users, particularly pedestrians (especially those with visual impairments), and cyclists. Consequently, there is a growing need to identify appropriate countermeasures to mitigate these risks effectively (Verheijen and Jabben. 2010). Range anxiety is not only a barrier towards the adoption of electric vehicles (Coffman et al., 2017) but it can also impede the safety performance of these vehicles. Concerns over the limited battery range could prompt some groups of drivers (especially the most aggressive ones) to engage in aberrant driving behaviors, such as

speeding or traffic signal violations, in their efforts to conserve battery power (Yuan et al., 2018).

Overall, over the recent years, a number of studies (to name a few, Nitsche et al., 2014; Yang et al., 2020; Botton et al., 2021) have investigated the safety aspects of electric and hybrid vehicles in various road networks. Despite extensive research ad-dressing various safety concerns, such as accident-avoidance strategies related to electric vehicle batteries, risks of electrocution stemming from the electrical systems, and the impact of low-frequency noise emissions on other road users, a notable gap exists regarding the behavioral patterns of users of electric and hybrid vehicles and their contribution to traffic accidents. Moreover, there is a dearth of information regarding the socio-demographic profiles of the users and how such vehicles interact within the con-text of existing road infrastructure. Therefore, there is a need for more empirical evidence on the factors determining the multi-faceted dimensions of accidents involving electric and hybrid vehicles. The present study aims to explore all these factors that can potentially influence the injury severity of accidents involving electric and hybrid vehicles. The novelty of this study lies in its comprehensive approach, integrating accident, geometric, vehicle, environmental, and socio-demographic characteristics within a single dataset to investigate accidents involving low-emission vehicles. Due to the limited availability of such integrated data in safety literature, this study aims to offer new insights into the underlying mechanisms of accident generation, particularly in the context of advanced technological innovation expected to dominate future car fleets.

2 Data

To identify the severity determinants of accidents involving electric and hybrid vehicles, injury severity data was drawn from the STATS19 dataset of the United Kingdom (Department for Transport, 2023). STATS19 is a public database that contains rich information regarding the accidents occurred in Great Britain and recorded by the police, such as the date, time, location, vehicles involved, types of road users, severity of injuries, and contributing factors such as road conditions, vehicle maneuvers and weather. The STATS19 dataset has been extensively used in previous accident injury-severity studies (Lyons et al., 2008; Imprialou and Quddus, 2019; Fountas et al., 2022). For this study, data from accidents occurred in Scotland (part of the United Kingdom) between 2010 and 2018 has been processed and statistically analyzed. By the end of 2010, there were around 135,000 electric or hybrid-electric cars in the UK (Department for Transport, 2011), whereas by the end of 2018, more than 620,000 vehicles were in use on the UK roads (Fleet News, 2019) According to the typology of the STATS19 database, the severity of accidents is recorded in three distinct, injury levels: slight, serious, and fatal injury. Upon a preliminary analysis of the accident data over the aforementioned period, it was identified that in 216 accident records, electric or hybrid vehicles were involved.

As earlier stated, the data used for the preparation of Fig. 1 were drawn from the STATS19 database (Department for Transport, 2023). Hybrid vehicles (which mainly refer to hybrid-electric vehicles) represent 88.43% of the sample, whereas the rest 11.57% of the sample consists of accidents involving electric vehicles, as also shown in Fig. 1. The predominance of the hybrid vehicles in the pool of observed accidents is

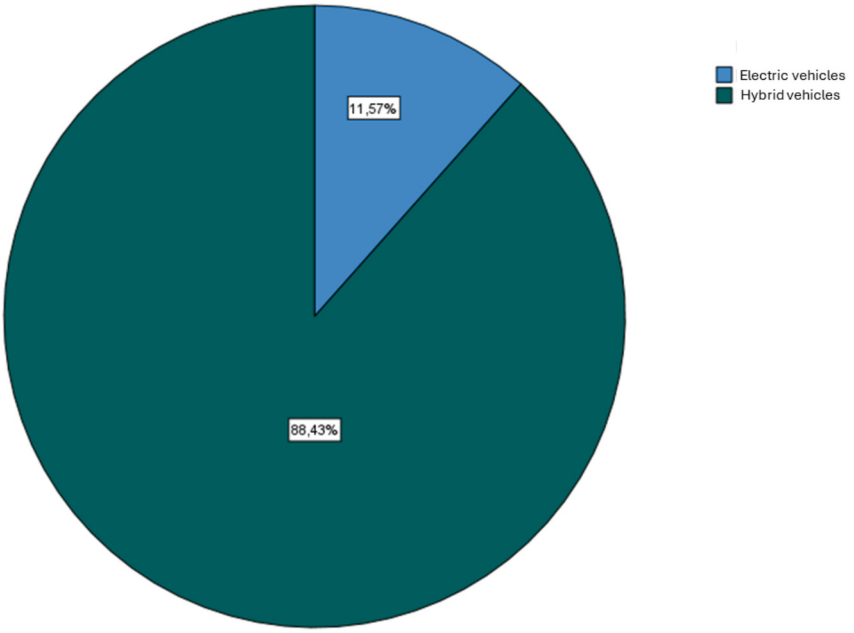

Fig. 1. Distribution of low-emission vehicles involved in accidents per their specific type

intuitive and can be attributed to their relative higher share in the car fleet compared to the fully electric vehicles (Department for Transport, 2011). As to the injury severities, the largest share of the sample is comprised of minor injuries (79.17% of accident records), followed by serious injuries at 19.44%, and fatal injuries with a very small percentage of approximately 1.39%. These injury severity statistics are in line with previous evidence from the same area (Fountas et al., 2020).

3 Methods

To identify the factors affecting the determinants of injury severities of accidents involving low-emission vehicles (i.e., electric and hybrid vehicles), a comprehensive data analysis was carried out comprising of three separate stages: (i) descriptive analysis; (ii) inferential statistical analysis and (iii) statistical modeling. The computation of descriptive statistics (e.g., mean, percentages, frequencies, etc.) is usually considered as the first step in data analysis and can assist in understanding the distribution of data and in preparing the data and variables for further statistical analysis (Fisher and Marshall, 2009).

The inferential statistical analysis refers to the process of inducing general conclusions or rules from a dataset and deal with the estimation, hypothesis, and generalization of results from a sample to a general population (Daniel and Cross, 2018; Basbas et al., 2020). Hypothesis testing is a key sub-category of inferential statistics. The selection of hypothesis test that will be leveraged to check whether there exists any statistically

significant association between a dependent and independent variable is subject to the type of the compared variables. In this study, the dependent variable is the injury severity outcome, which can take three categorical values (slight, serious, and fatal injury) and can be placed in an ordinal severity scale. As such, the dependent variable is ordinal and discrete in nature, therefore, only non-parametric tests can be considered. The independent variables (i.e., the variables representing potential determinants of injury severities) are either nominal or ordinal in nature. To that end, the chi-square and Friedman tests were carried out to identify any potential relationships. The chi-square test can help identify potential associations between categorical variables, whereas the Friedman test can provide even more specific insights when the compared variables are ordinal in nature.

Given that the inferential statistics can provide insights only about possible associations between pairs of variables, a statistical model is needed to gain a more comprehensive understanding of the factors affecting the injury severities of accidents involving electric or hybrid vehicles. In contrast to inferential statistics, the estimation of a statistical model entails recognizing the direct influence of each independent variable on the dependent variable, while concurrently accounting for the effects of all other variables considered within the model (Tsavdari et al., 2022). For the estimation of the injury severity model, the Generalized Linear Model (GLM) was selected as an appropriate modeling approach. The generalized linear model extends the traditional linear model, enabling the dependent variable to be associated with both categorical factors and independent continuous variables. Moreover, the model accommodates a non-normal distribution for the dependent variable. The GLMs encompass widely utilized statistical models, including linear regression for normally distributed responses, logistic models for binary data, log-linear models for count data, as well as various other statistical models through their highly flexible formulation. In this study, the sample and the dependent variable does not adhere to a normal distribution; as such and given the ordinal nature of the dependent variable, an ordered probit model was selected as an appropriate approach to identifying the injury-severity determinants (Washington et al., 2020). It should be noted that all the statistical analyses presented in this paper were carried out using the software package IBM SPSS Statistics 28.0.

4 Results

4.1 Key Descriptive Statistics

Starting with the socio-demographic characteristics of the vehicle drivers involved in the accidents, 68.06% of the drivers were males, whereas female drivers were observed in 31.48% of the cases. As to the age of the drivers, the mean age of the driver was 46.5 years old, with the majority of the drivers' ages ranging from 26 to 65 years old. 3 out of 4 accidents involving electric or hybrid vehicles occurred on a single carriageway (unseparated road with a single lane per direction), whereas almost 14% of the accidents were observed on dual carriageways (roads with directions separated through a central median). With respect to the accident location, the vast majority of accidents (67.59%) occurred in urban areas. Focusing on particular roadway features of the accident location, 4 out of 10 accidents were not located on or close to a junction, whereas almost 30% of the observations were associated with a T or a staggered junction. As to the road

surface conditions, most of the incidents (63.43%) took place on a dry pavement, and almost 34% of them were linked with a wet pavement surface. Considering the vehicle maneuver at the time of the accident, 43% of the accidents occurred while the vehicle was traveling straight ahead, whereas 17.6% of the sample consists of accidents during right-turn maneuvers. In 64.35% of the cases, the first point of impact in the course of the accident was at the front of the vehicle Another important vehicle characteristic is related to the engine capacity, with the descriptive statistics showing that 45% of the vehicles involved in the crashes had engine capacity greater than 1400 cc; however, it should be noted herein that for 11.5% of the cases, information about engine capacity was not available in the dataset. Finally, with regards to the prevailing environmental conditions at the time of the accident, approximately 3 out of 4 accidents occurred under fine weather and daylight conditions.

4.2 Inferential Statistical Analysis

Table 1 presents the results of the inferential statistical tests that were conducted to identify potential associations between the injury severities of accidents involving electric or hybrid vehicles and roadway-, vehicle-, driver- or environment-related factors. As shown in the Table, the p-value of all tests (both chi-square and Friedman tests) was lower than 0.01, thus suggesting the presence of statistically significant relationships between the accident injury severities and these factors at a minimum 99% level of confidence.

The relationships of other variables with the accident injury severity were also investigated through statistical tests, but they turned out to be statistically insignificant.

4.3 Ordered Probit Model

As earlier mentioned, while the inferential statistical tests can give some insights into the pair-wise comparisons of the injury severities with established safety determinants, they cannot account for the simultaneous impact of other factors on the dependent variable. Therefore, the inferences of such tests may be subject to bias. To gain a more comprehensive understanding of the concurrent effects of several factors on accident injury severities, an ordered probit model was estimated. The results of the model are presented in Table 2. All the independent variables are statistically significant at a minimum 90% level of confidence, as indicated by the corresponding p-values. For the model estimation, all the available and relevant variables were tested, but only those included in Table provided statistically significant results. The goodness-of-fit of the model was also thoroughly evaluated through Likelihood Ratio Tests (LRTs).

Overall, two characteristics related to road geometry (road type and speed limit) and one environmental attribute (weather conditions) were identified to exert a significant impact on accident injury severities. By comparing the parameters of all explanatory variables included in the model, it is evident that the two geometric characteristics have a stronger influence on injury outcomes. Driver characteristics (e.g., age, gender, and so on) were also tried as potential independent variables in the model, but their impact was identified as statistically insignificant.

Table 1. An overview of the results of the inferential statistical tests

Dependent Variable	Independent Variable	Statistical Test	p-value
Injury severity outcome (slight injury, serious injury, fatality)	Road type (One way street, dual carriageway, single carriageway, slip road, roundabout)	$\chi 2$ (chi-square)	$p < 0.01$
	Speed limit (20mph, 30mph, 40mph, 50mph, 60mph, 70mph)	$\chi 2$ (chi-square)	$p < 0.01$
	Junction type (Not at junction or within 20 m, roundabout, mini-roundabout, T or staggered junction, crossroads, more than 4 arms (not roundabout), private drive or entrance, other junction type)	$\chi 2$ (chi-square)	$p < 0.01$
	Lighting conditions (Daylight, darkness - lights lit, darkness - lights unlit, darkness - no lighting, darkness - lighting unknown)	$\chi 2$ (chi-square)	$p < 0.01$
	Weather conditions (Fine no high winds, raining no high winds, snowing no high winds, fine and high winds, raining and high winds, snowing and high winds, fog or mist, other)	$\chi 2$ (chi-square)	$p < 0.01$
	Road surface conditions (Dry, wet or damp, snow, frost or ice, flood over 3cm. Deep oil or diesel, mud)	$\chi 2$ (chi-square)	$p < 0.01$
	Pavement hazard	$\chi 2$ (chi-square)	$p < 0.01$
	Accident location (urban, small town, rural)	$\chi 2$ (chi-square)	$p < 0.01$
	Vehicle maneuver (Reversing, parked, slowing or stopping, U-turn, turning left, turning right, changing lane, overtaking, going ahead)	$\chi 2$ (chi-square)	$p < 0.01$
	Vehicle's point of impact (Did not impact, front, back, offside, nearside)	$\chi 2$ (chi-square)	$p < 0.01$
	Driver's gender (male, female)	$\chi 2$ (chi-square)	$p < 0.01$

(*continued*)

Table 1. (*continued*)

Dependent Variable	Independent Variable	Statistical Test	p-value
	Driver's age range (0 – 5, 6 – 10, 11 – 15, 16 – 20, 21 – 25, 26 – 35, 36 – 45, 46 – 55, 56 – 65, 66 – 75, Over 75)	Friedman	$p < 0.01$
	Vehicle's engine capacity (in cc)	Friedman	$p < 0.01$

Table 2. Estimation results of the ordered probit model.

Variable	Parameter (B)	Wald Chi-square	Degrees of freedom	p-value
Threshold 1	23.845	–	–	–
Threshold 2	26.179	–	–	–
Speed limit = 20 mph	−3.342	−6.123	1	0.035
Slip road	4.213	9.405	1	0.002
Fine weather with high winds	2.454	3.420	1	0.064

As shown in Table 2, accidents occurring on roads with 20mph speed limit are less likely to result in fatal injuries. The sign of the coefficient is negative, which implies a lower likelihood of fatal injuries. This result may reflect the effect of reduced speeds that are observed in roads with 20mph speed limits (Olowosegun et al., 2023). Furthermore, 20mph roads have been found to lead to the mitigation of severe road casualties (Cleland et al., 2020), which seems to be also confirmed in the case of electric and hybrid vehicles.

As shown in Fig. 2, the vast majority of accidents occurring on 20mph roads (almost 82%) resulted in a slight injury, whereas for higher speed limits, the proportion of serious and fatal injuries is significantly higher. Fatal injuries are observed on accidents occurring on roads with 30mph (which represent almost 60% of the accidents in the dataset) and 60mph speed limit (representing approximately 22% of the accident in the dataset). In fact, most accidents (approximately 82%) on 60mph roads result in fatal and serious injuries, which is a quite concerning finding as to the safety performance of low-emission vehicles on high-speeds roads (such as dual carriageways). Similar patterns are evident on 70 mph roads (typically motorways and dual carriageways), with 62% of accidents yielding serious injuries, but no fatalities. Accidents on 20mph roads account for a bit less than 10% of the sample, whereas it is notable than no fatal injuries were observed on these roads; this finding further highlights the crucial role of low speed limits for the implementation of the Safe Systems Approach, which puts emphasis on the elimination of serious and fatal injuries (Karndacharuk and McTiernan, 2019).

In contrast, the variables "slip road" and "fine weather with high winds" are associated with a higher likelihood of fatal injuries, as the corresponding sign of the coefficient is positive. That means that accidents that involve electric or hybrid vehicles and occur

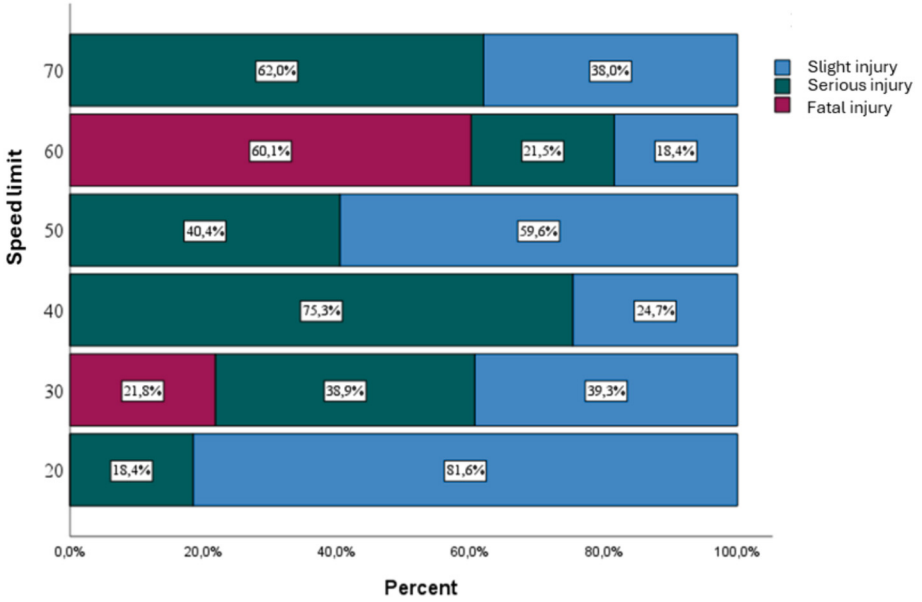

Fig. 2. Distribution of accident injury severities across roads with different speed limits (in miles per hour – mph)

on slip roads (e.g., exit or entrance ramps of highways) or under fine weather conditions but with high winds are associated with more severe injuries. Fine weather may induce risk-compensating effects, thus prompting drivers to indulge in more aggressive driving patterns, as also suggested by previous research (Mannering and Bhat, 2014). Lastly, the combination of limited space on slip roads and the complexity of maneuvers that are required due to merging and diverging traffic (to or from the highway) can make accidents on slip roads more likely to result in severe injuries compared to accidents on other types of roads.

5 Discussion and Conclusions

This study sought to deliver new empirical evidence on the injury severities of accidents involving electric or hybrid-electric vehicles and their determinants. Despite the small sample size, the analysis shows that the majority of accidents involving such low-emission vehicles resulted in slight injuries. The descriptive analysis showed that a significant proportion of accidents involve more male drivers compared to females, with a disparity of approximately 30%. Moreover, high proportions of drivers involved in accidents are evident within the age brackets of 26–35, 36–45, and 45–55. Given that drivers of such ages are more likely to use electric or hybrid vehicles, this finding highlights the necessity for informing and sensitizing drivers of these age groups to acquaint themselves not only with new vehicle types but also with updated road safety practices.

Furthermore, a considerable proportion of accidents are observed on unseparated roads featuring a single lane per direction; on such roads, traffic directions are distinguished through pavement markings rather than median strips. In addition, most accidents were identified in urban areas, which can be attributed to the high presence of electric and hybrid vehicles navigating within urban environments. This finding also serves as an alert for a more intensive infrastructure development for electric vehicles in urban areas as well as for a holistic integration of low-emission vehicles with the smart infrastructure of cities to enable better traffic management and accident prevention.

Regarding the vehicle maneuver characteristics, most accidents occurred when the vehicles were traveling straight ahead and not on or close to junctions. Hence, most accidents occurred when drivers did not have to undertake complex maneuvers, though other distractions (internal or external) might play a notable role. It is acknowledged that contemporary electric and hybrid vehicles may include features such as touch control panels or large screens facilitating camera usage, map navigation, or mobile phone connectivity, potentially diverting the driver's attention from the driving task. The incorporation of more disruptive Advanced Driving Assistance Systems (ADAS) within low-emission vehicles could also help tackle the safety implications of driving distractions.

The results of the inferential statistical analysis and the ordered probit model unveiled valuable insights into the interaction between several roadway- and environment-related variables and the injury severity of accidents. Notably, the posted speed limit, and particularly lower speed limits (20 mph or 30 km/h), emerged as significant influencing factors of accident severity. This finding highlights that electric and hybrid vehicles have a satisfactory safety performance in low-speed environments, as the likelihood of severe or fatal injuries reduces. A safety-related synergetic effect seems to underpin the use of low-emission vehicles in traffic calmed area; this potential implication warrants further investigation in the future, as, once confirmed, it can help local Authorities better co-ordinate their efforts in not only reducing vehicle emissions, but also improving the level of road safety, especially in built-up areas. Weather conditions were also identified as a major influencing factor with accidents occurring under fine weather and high winds favoring greater injury severity. This result suggests that the risk-compensating behaviors of drivers under varying environmental conditions, are not only important for drivers of conventional vehicles, as suggested by previous research (e.g., Fountas et al., 2020) but they can also affect the safety performance of drivers of electric or hybrid-electric vehicles.

This study is one of the first attempts to profoundly understand the relationship between electric and hybrid vehicles and key contributing factors of traffic safety. The expansion of research into new-age, low-emission vehicles stands to yield considerable benefits. As time progresses, it becomes increasingly apparent that the automotive fleet undergoes a continuous integration of novel electric and hybrid vehicles. Considering that this study was conducted on the basis of limited accident data, the use of a broader sample size in the future could enable the refinement of models tailored to address users' requirements for increased safety within road networks. Furthermore, the administration of surveys pertaining to perceptions of safety of electric and hybrid vehicles could furnish insights from the users' standpoint, thereby facilitating a more exhaustive investigation.

Disclosure of Interests. The authors have no competing interests to declare.

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Planned and Implemented Actions by Exercises

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Abstract. On a global scale, natural and man-made disasters cause significant losses. For this reason, disaster risk reduction is a priority. This paper focuses on the exposure risk component during the occurrence and evacuation planning. There is a gap between the planned actions and their implementation during real emergency conditions. From the proposed reviewed literature different lacks emerge, including the evaluation of the risk reduction produced by each exercise or training actions. To build a bridge above this gap, it is necessary to design and experiment with training and exercises for putting into practice the planned evacuation procedures. A method is proposed to evaluate the exposure reduction by means of these actions. The literature distinguishes two main classes of actions: discussion-based, aimed at reviewing evacuation plans and procedures; and operation-based, aimed at simulating real experimentations with decision-making and people involved in a potential emergency situation. The expected outcome is to increase awareness of managers and users about the evacuation procedures for pursuing the final goal of exposure and therefore risk reduction. With increasing complexity and capabilities, exercises and training contribute to increasing the effectiveness of the planned actions. The paper is useful for risk managers and public decision-takers involved in the evacuation planning process to increase preparedness before an emergency event.

Keywords: disaster risk · risk reduction · evacuation planning · exercises

1 Introduction

On a global scale, natural and man-made disasters cause significant losses. In 2022, the Centre for Research on the Epidemiology of Disasters (CRED) estimates around US$223.8 billion deriving from recorded 387 natural hazards and disasters worldwide, with effects on 185 million individuals [1]. According to Sustainable Development Goals (SDG) and relative targets of the Agenda 2030 (SDG 1 – "End poverty in all its forms everywhere"; SDG 11 – "Make cities and human settlements inclusive, safe, resilient and sustainable"; SDG 13 – "take urgent action to combat climate change and its impacts") [2], there is a clear need to plan and implement a set of actions and policies for disaster risk reduction. This implies the necessity to define an emergency planning process and products to design a system that minimises risk and its three components [3]: occurrence, related to the probability or frequency that an emergency event happens; vulnerability related to the probability that the system resists to the effects produced by the event; exposure related to the number of people affected by the effects.

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The emergency planning products must support decision-takers to manage the transition of the system from a generic plan for the ordinary conditions (P_0) to a planned configuration that minimizes risks (P_{min}) in the extraordinary conditions [4], where for each plan there is a different level of exposure and risk. This paper focuses on evacuation planning for reducing the exposure risk components and then the actions on the components of a transport system, including [5]: material actions that modify the physical asset of transport infrastructures; immaterial actions that regard, from one side, the Information and Communication Technologies (ICT) [6–8] and, from another side, education, training and exercises of managers and users [9]; management actions for organising transport systems in evacuation conditions [10, 11]; equipment actions that regard means and tool for performing an evacuation.

This paper focuses on the immaterial actions aimed at increasing preparedness with training and exercise actions. These actions contribute to reducing distances between the planned configuration P_{min} and the real implementation when disaster occurs. In this context, training and exercises play a relevant role because their implementation increases awareness of people and managers about the planned procedures for performing an effective evacuation (outcome) and reducing exposure (final goal).

According to Russo and Rindone [9], the implementation of a generic exercise's activity (T_j), produces effects in terms of exposure, quantifiable with the variable $E(T_j)$. The expected outcome of each activity T_j is the awareness enhancement of managers and users involved in the risk situation, tending to reach the exposure level planned with P_{min} and quantifiable with the variable $E(P_{min})$. The exposure reduction contributes to reducing the number of direct and indirect people affected by disasters, in line with SDG targets (see for instance the SDG target 11.5 and related indicators 11.5.1).

In this context, the paper offers the following research contributions:

- a methodology to evaluate the reduction of exposure through training and exercise actions;
- an overview of the possible training and exercises for experimenting with the planned actions.

After this introduction, the paper has three sections. Section 2 presents a methodology for specifying actions that contribute to risk reduction. Section 3 presents some experimental indicators for measuring the contribution of exercise and training actions to risk reduction. Section 4 gives quantitative values for some implementations with final remarks and further developments of the research.

2 A Method for Specifying Actions for Risk Reduction

2.1 Actions for Each Scenario

Reducing exposure is a key element for reducing risk. As seen, exposure can be reduced directly by adopting and implementing appropriate evacuation plans.

To obtain the expected results in the evacuation plan, it is necessary that in the time that elapses between the extension of the plan and the occurrence of the event and therefore of the effects, various exercise and training activities must be carried out. This time is indicated with Δ.

Scenario S is defined by the generic natural or man-made event and by the effects, resulting from the event, on the population, fixing the probabilities of occurrence and vulnerability. In dangerous events, different occurrence levels can be considered from earthquakes to floods and tsunamis (natural), from terrorist attacks to transportation of dangerous goods (man-made).

We indicate with E_0 the aggregate exposure value in ordinary conditions of supply and demand of plan P_0, with E_{min} the minimum exposure value of plan P_{min}, both calculated in the generic risk scenario S by a "what if" planning process, through a system of TSM models.

It is assumed to perform different actions of training and exercise in time period Δ.

Each action affects different subjects and can be developed in different places and at different times (inside Δ) with different managers and different users. It is assumed that the different actions can be identified and that the results of the actions in terms of exposure reduction are independent.

Given a generic scenario S it is possible to specify the general actions present in the literature and in practice for scenario S. Thus, for each scenario S a set of nominally defined actions can be defined in the vector $\mathbf{a}^S$.

$$\mathbf{a}^{\mathbf{S}} = (a_1^s,\ a_2^s,\ \ldots,\ a_{k,}^s \ldots,\ a_n^s)$$

where $a^s{}_k$ is the generic action k to implement for the risk defined by scenario S and n is the total number of actions you want to implement.

As seen in Sect. 1, in the scientific and technical literature, different actions are proposed.

A first problem that arises is that each State specifies these actions differently in its legislation by associating different names.

A second problem, previously mentioned, is that in different States the focus is more on the actions that can be implemented "after" the event. In other States, much importance is given to actions that can be implemented "before" the event. In this second group there is the US.

A third problem is that the actions defined in the regulations of each State, often have overlapping activities, so it is not possible to attribute the results in terms of exposure reduction, to one or another action.

It is therefore necessary to recall the names of the most widely used actions in the "before" approach present in the literature and in the regulation, having to propose here advanced definitions and examples, in order to guarantee the previously introduced hypothesis of independence of the results. It is therefore necessary to identify the central nucleus of each action in order to create a clear separation between the results of the different actions and to obtain specific indicators.

2.2 Training and Exercises Indicators of Exposure Reduction

The theme that arises is to identify a set of indicators that can enable the measurement of exposure reduction and that can be applied in whole or in part to the different actions of exercise and training.

It is necessary that the values of the indicators can be estimated before and after the action is carried out in order to highlight the contribution that the specific action makes to reducing exposure.

It follows therefore that a vector of exposure indicators can be specified whose values can be calculated before and after the implementation of a^s_k generic action.

It is possible to define a function $g_h(\cdot)$ that allows the calculation of the generic indicator e^s_h, based on the effects of the generic action k:

$$e^s_h = g_h\left(a^s_k\right) \tag{1}$$

where the generic e^s_h indicator, of the $\mathbf{e_s}$ vector, is estimated leaving from the effects of the a^s_k action.

Based on Eq. 1 it is possible to define a vector function **g** whose values represent the identified indicators.

By introducing the hypothesis of independence of the results of the different actions and defining an aggregate function of exposure given by the combination of the different indicators it is possible to estimate an exposure level "before" the action:

$$E^s_{before} = f\left(\mathbf{e^s}\right) = f(g\left(a^s_1,\ a^s_2,\ \ldots,\ a^s_k = 0,\ \ldots,\ a^s_n\right) \tag{2}$$

where

$f(\cdot)$is the aggregate exposure level function;

a^s_k is the activity k that you want to implement, and that therefore conventionally is indicated as zero in the before condition;

a^s_1, a^s_2, a^s_n, are the activity-related values that have been, or will be implemented in the future but are not implemented at this stage.

In the same way, it is possible to calculate the aggregate function "after" the implementation of the action:

$$E^s_{after} = f\left(\mathbf{e^s}\right) = f(g\left(a^s_1,\ a^s_2,\ \ldots,\ a^s_k \neq 0,\ \ldots,\ a^s_n\right) \tag{3}$$

with the same meanings previously defined, where only a^s_k for changes precisely because it is the action implemented.

It is possible to exemplify the formulations introduced, assuming that the indicators defined by the vector $\mathbf{e^s}$ are all decreasing and also assuming that the aggregate value of E^S both before and after, is given by a function f ($\mathbf{e^s}$) defined by an algebraic sum. It is possible to exemplify the functions with the hypotheses:

- the indicators defined by the vector $\mathbf{e^s}$ are decreasing as exposure decreases;
- the decrease of each indicator h relative to the implementation of the action k in scenario S, is indicated with d^s_{hk};
- the aggregate value of E^S is given by an algebraic sum of the (decreasing) indicators.

In these hypotheses in whichever state of advance of the actions, from the approval of the plan (no implemented action) forward results:

$$E^S = \sum_{hk} d^s_{hk} \tag{4}$$

The value of Eq. 4 can be calculated:

- for the different actions;
- for the different advances that can be made for the same action;
- in the conditions before and after the implementation of all the action or only part of the action.

More complex functions than Eq. 4 can be used, but the expression considered has both the ability to be easily implemented and the ability to be easily checked in the results.

The methodology presented in this section can be applied to any system of actions proposed by the generic State. One of the most integrated share systems is the one developed in the US [12].

3 Experimental Indicators of Exercise and Training Actions to Risk Reduction

3.1 Class and Characteristics of Activities

Different States have produced procedures for exercise and training. However, the most complete structure present in the literature seems to be the one developed in the US [12]. The same fact of being the most present in the literature confirms that the US framework is the most capable of guaranteeing, to date, the best preparedness.

The central theme of all the actions that develop in the preparedness phase is how a virtual environment with respect to the risk (in the sense that the real event did not happen) can allow the increase of knowledge in all the subjects involved: from the casual and systematic users of the study area to disaster managers of various levels of responsibility.

For each exercise and training activity to be carried out in virtual conditions, defined by any State, the main characteristics to be studied are (Fig. 1):

- the *capability*, evaluated as the ability, or the capacity, to intervene in real conditions to reduce exposure, and therefore the possibility of expressing an indicator of pursuit of the reduction objective;
- the *complexity*, evaluated as the quantity and type of actors involved in the specific activity.

In the methodological hypotheses made and following the two main characteristics identified above, it is possible to introduce an aggregation into two main classes of all the implementable actions.

The first class is defined in a homogeneous way by the activities that can be carried out in an enclosed and indoor environment and which do not require all the real environments in which the effects of the scenario considered can evolve. The main focus of this class is given by the discussion which is developed in various ways and with material and immaterial tools available. They are therefore usually defined as *discussion-based* activities. In these activities, complexity evolves with the growth in the number of actors present, while capability evolves with the specific ability to reduce exposure. In the US

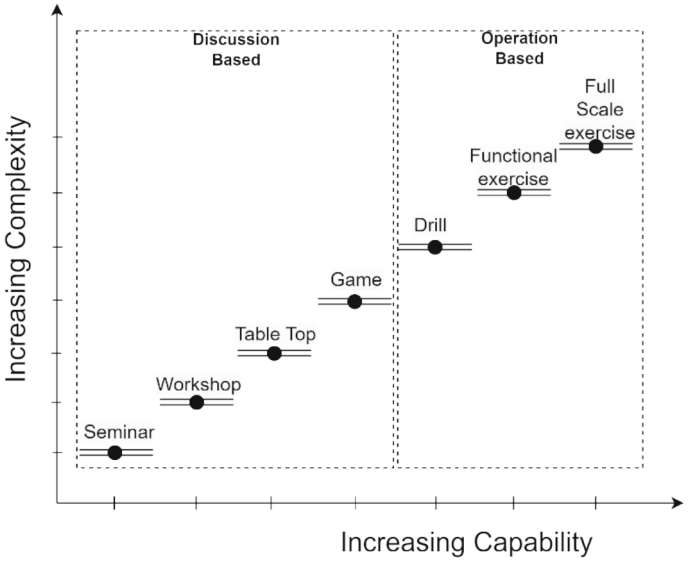

Fig. 1. Classes of exercises

approach, four actions are identified, which can be implemented with different levels of complexity: seminars, workshops, tabletop exercises, games.

The second class is homogeneously defined by the activities that must be carried out in the real environment in which the effects of the scenario considered take place. The focus of this class is given by the operations which are organized in various ways and with various material and immaterial tools available. They are therefore usually defined as *operation-based* activities. Even in these activities, complexity evolves with the growth in the number of actors present, while capability evolves with the specific ability to reduce exposure. In the US approach, three main actions are identified, which can be implemented with different levels of complexity and with the participation of different classes of actors: drills, functional exercises and full-scale exercises.

3.2 Discussion-Based: Seminars

A seminar is a training activity based on the development of an informal discussion about existing plans and procedures. For these uses, discussion-based exercises are exceptional tools for familiarizing organizations and personnel with current or expected capabilities. The seminar is designed to orient participants to familiarize themselves with new or updated plans, policies, or procedures (e.g. a seminar to review the transit agencies' roles in evacuating a group of schools). Seminars focus on the defined evacuation procedures and the case studies. The seminar involves a small group of actors playing a relevant role in a potential emergency situation comprehending emergency managers and citizens. The seminar is characterized by limited interactions between the presenter (PR) and the audience (AU). The communication is only one direction from the presenter to the audience. The activities of a seminar are "lecture-based" and consist of the presentation

of the plan finalized to review of planned actions and procedures. The main output is a review report that indicates the proposal for improving the plan contents. The results of a seminar constitute the starting point for the next exercises or training actions. After a seminar, it is possible to perform qualitative evaluations of the planned emergency procedures.

The Economic Commission for Latin America and the Caribbean (ECLAC) of the United Nations illustrates the main results of an evaluation of seminar activities aimed at orienting policymakers and professionals involved in disaster risk management [13].

A reference indicator for evaluating the reduction in exposure produced by a seminar for the scenario *s* can be given by:

$$e^{S}_{sem} = \textit{time needed for the individual to acquire the plan documentation}$$

The specific indicator can be evaluated with respect to the different hierarchical levels of disaster management [14]. The indicator can also be calculated for different types of users belonging to the population.

The indicator thus specified is easily scalable with respect to the number of participants in the generic seminar. Assuming that the final target is the N_{sem} quantity of managers and users, the indicator has the characteristics defined above capability and complexity.

3.3 Discussion-Based: Workshops

A workshop is a training activity based on the development of interactive discussion similar to a seminar. Compared with a seminar, the main difference consists in the final output which is produced as a draft plan or policy (e.g., a Training and Exercise Plan). The realization of a workshop implies an interaction between organizations (PR) and participants to obtain feedback from the audience (AU) about planned actions and procedures. In this case, there is a two-way communication. The main aim of a workshop is to obtain qualitative evaluations of the planned emergency procedures and their perception from the audience.

Sometimes, seminars and workshops are named "orientation exercises" indicating the actions with the lowest level of complexity, involving the minimum quantity of resources. The main aim is to review and validate existing plans or plans under development, by means of simulation exercises as a part of the preparedness process [15].

A reference indicator to evaluate the reduction in exposure produced by a workshop for the scenario *s* can be given by:

$e^{s}{}_{work}$ = *time needed for the subject to produce the documentation for the official information to be transmitted during the event*

The specific indicator can be evaluated with respect to different hierarchical levels of disaster management. The indicator is calculated both for those responsible for the overall evacuation of the area and for those responsible for the evacuations of individual buildings which perform different functions.

The indicator thus specified is scalable with respect to the number of participants in the generic workshop. Assuming that the final objective is the N_{wor} quantity of managers participants in the workshop, the indicator has the capability and complexity characteristics defined above.

Gwynne et al. [16] propose an "evidence-based" methodology for assessing evacuation drills, also in relation to the application of emergency technologies.

3.4 Discussion-Based: Tabletop Exercises

A tabletop exercise (TTE) is a training activity based on the development of an emergency scenario, simulated in an informal setting. The main objective is to assess plans, policies, and procedures experimenting with roles, procedures, and responsibilities in the emergency management system. TTE allows participants to experiment with the decision-making processes and procedures by means of a discussion about the agency procedures, developed along a hypothetical timeline of actions and events, and identify priorities for evaluation during the full-scale exercise. The TTE involves the key personnel in discussing the scenario evolution, attempting to approximate the real emergency situation. Other than the presenter and the audience, there are:

- a facilitator (F) that stimulates the discussion between emergency managers and participants;
- an evaluator (E) that observes the exercise and collects data and information by means of a survey.

The main aim of a TTE is to perform quantitative evaluations about the potential effects produced by the planned emergency procedures. Sometimes, TTE is recommended as a preparative activity of a complex operation-based exercise [17].

A reference indicator to evaluate the reduction in exposure produced by a tabletop for the scenario s can be given by:

$e^s_{TTE,1}$ = *time needed to exchange information between emergency managers in the management chain for starting the evacuation procedures during the event*

$e^s_{TTE,2}$ = *time needed to communicate population the evacuation order*

The proposed indicators evaluate the level of efficiency of communications and information in the evacuation management process. The indicator $e^s_{comm,1}$ refers to the efficiency in the immaterial exchanges in the command chain. The indicator $e^s_{comm,1}$ refers to the efficiency to disseminate information to population about performing the evacuation. Assuming that the final objective is the Δ_1, the available time interval before instant when the threat occurs [10], the minimization of percentage of $e^s_{TTE,1} + e^s_{TTE,2}$, respect to Δ, contribute to minimize the exposure.

Mat Said et al. [18] present the results of a TTE for verifying tsunami evacuation planning in terms of routes, safe zones and warning protocols with the aim to increase preparedness's community.

Skryabina et al. [17] analyze the potential impacts of the exercises in relation to three terrorist attacks occurred in the UK in 2017 (e.g. the Manchester Arena bombing). The results obtained from the performed surveys demonstrated that TTEs exercises have positive direct impacts during a real incident, in terms of response's times reduction and then increased number of saved lives.

3.5 Discussion-Based: Games

A game is a training activity based on the development of a simulation of emergency operations performed by two or more teams (at least composed by only one person), usually in a competitive environment. The game reproduces a realistic and immersive emergency scenario. The main objective of a game is to use rules, data, and procedures designed to represent a real-life situation, derived from an emergency event. Sometimes a game is a combination of Virtual Reality (VR) and Serious Games (SG) performed to expose involved people to emergency scenarios in a virtual context without any real risks [19]. Like the tabletops, a game aims to perform quantitative evaluations with the support of advanced technologies enabled for measuring further variables about managers and audiences.

The indicators to evaluate the reduction in exposure produced by a game for the scenario *s* can be given by:

$e^s{}_G$ = *time needed to evacuate people (or only one person) in the virtual environment*

where $e^s{}_G$ is the registered time during the game to simulate the evacuation procedure. The time can be disaggregated in relation to each phase of the evacuation procedure. Some examples of performance indicators for a game are reported in Chu et al. [20], by referring to an emergency evacuation simulation in a portion of an urban context. The authors simulate the evacuation time of a single building and of a set of neighborhood roads.

Kwegyir-Afful et al. [21] studied the effects produced by simulation in an immersive virtual reality for testing the fire emergency preparedness and response in a gas power plant. The game exercise simulates an evacuation drill in a fire emergency simulation scenario.

3.6 Operation-Based: Drills

A drill is the simplest operation-based training activity based on the simulation of a single function within a single entity (e.g., a civil protection unit conducts a decontamination drill). Drills are aimed at testing and evaluating the performances of the observed function and relative entity. A drill involves people and managers of a single organizational unit, responsible for the tested function. Sometimes a drill exercise can be performed with the support of a mobile application used as an educational tool. Leelawat et al. [22] analyse the results of a drill for simulating a tsunami emergency scenario. The mobile tool is useful for collecting information about changes in the behaviour of the participants and decision-makers, in relation to different inundation scenarios of relative travel choices (e.g. evacuation routes and destinations).

A reference indicator to evaluate the reduction in exposure produced by a drill for the scenario *s* can be given by:

$e^s{}_D$ = *time needed to conclude planned emergency operations performed by managers*

The proposed indicators evaluate the level of efficiency of single functions in the evacuation management process (e.g. decision making, communication, dissemination, evacuation execution, emergency care activation…). The proposed indicator can be measured in a context without a plan, for instance in an ordinary condition, and after the execution of a drill.

3.7 Operation-Based: Functional Exercises (FE)

A Functional Exercise (FE) is an interactive operation-based exercise that simulates the progress of a hypothetical emergency scenario. FE replicates a system in an emergency condition for testing in a real context with the use of resources and equipment. FEs are aimed at validating procedures of coordination, command, and control between various multi-agency (e.g., urban emergency centres, safety office of a public administration). FE evaluates the organization's capacity to respond to an emergency situation, assessing at the same time, the eventual lack of available resources. FE can be propaedeutically, or a full part, to the realization of a Full-Scale Exercise.

A reference indicator to evaluate the reduction in exposure produced by a FE for the scenario *s* can be given by:

e^s_{FE} = *time needed to evacuate a homogeneous group of users (e.g. living in a single building, in a school, or in a portion of the study area)*

The proposed indicators evaluate the level of efficiency of all functions that have to be activated in the evacuation management process (e.g. decision-making, communication, transportation services for vulnerable people, emergency care activation, traffic management, and signalizing …). The proposed indicator can be measured in a context without a plan, for instance in an ordinary condition, and after the execution of a FE.

In 2013 the city of Los Angeles performed a FE to simulate and evaluate the response's capability in the case of a flood. The master scenario comprehends other sub scenarios, including for instance a road accident involving a dangerous good substance. The FE involved all emergency agencies of the city. The After-accident report indicates the strengths and the weaknesses of the involved organizations [23].

3.8 Operation-Based: Full-Scale Exercises (FSE)

A full-scale exercise (FSE) is a complex operation-based exercise that simulates a real emergency scenario, for testing more functions, performed by more organizations and involving more participants. This is the most advanced step of the HSEEP approach. FSE test procedures involve more organizations and disciplines at different territorial levels (e.g., hospitals, urban emergency centres, fire fighters, and emergency services). A FSE is performed in a highly stressful environment, usually conducted in real-time. The main aim is to reproduce as a "mirror" a real incident in order to evaluate the operational capability of emergency management systems. For these reasons, FSE implementation requires a large availability of resources in terms of personnel, equipment, and financial resources [24].

A reference indicator to evaluate the reduction in exposure produced by a FSE can be given by:

e^s_{FSE} = *total evacuation time of the defined population present in the disaster area*

The proposed indicators evaluate the level of efficiency of all evacuation management functions and the performances of the transport system in an evacuation condition [25]. The proposed indicator can be measured in a context without a plan, for instance in an ordinary condition, and after the execution of a FSE.

Lundh et al. [26] analyze the observations of five full-scale exercises performed in maritime transport passenger services.

4 Discussion and Final Remarks

To reduce the consequences produced by an increasing number of disasters on a global scale, it is necessary to plan and implement actions aimed at increasing preparedness. From the presented review, it emerges a difference in approaches to risk management. In the great part of the world, attention regards the actions for facing the "after" disaster situations. After relevant disasters (e.g. 9/11 terroristic attack and Hurricane Katrina) US introduced a standard approach aimed at increasing preparedness with a set of exercises. Evacuation plans play a relevant role in increasing preparedness and reducing risk. However, to increase the level of efficiency and effectiveness of planned actions, it is necessary to experiment with them in a no-stress context. For this reason, the planning process has to include the design and implementation of a predefined set of exercises for increasing awareness of managers and citizens about the planned actions for facing emergency situations. The final aim is to contribute to risk reduction. This paper focused on the evacuation exercises, planned and implemented for reducing exposure components. The paper illustrates the main functional schemes of each type of exercise, both with reference to the discussion-based and operation-based classes. For each exercise, examples of indicators are proposed to measure performance and to evaluate the possible contribution of the exercises to reducing exposure. However, in a worldwide context, there is a limited quantity of exercises experimented in real contexts for putting into practice the evacuation procedures of cities or their portions. Some experiences regard single buildings with a specific reference to the health sectors (e.g. hospitals). The potentialities offered by the interaction between Transport System Models and ICT enable the implementation of different typologies of exercises to collect information and support evaluations about the effects of planned procedures. The paper presents some limits in relation to the definition of targets for comparing the obtained values of the proposed indicators. For each kind of exercise, it is necessary to provide more insight about the modalities to perform the training activities and relative evaluation methods. The research can evolve following different directions. A first regards the designing process of each kind of exercises by defining involved actors (e.g. managers and people), needed resources and evaluation methods. A second regards the possibility to support exercises with emerging ICT tools enhanced with methods and models of TSM. Final research direction concerns the interactions with other scientific research contexts (e.g. phycology or health).

The obtained results are useful for risk managers and public decision takers involved in the evacuation planning process to increase preparedness before an emergency event.

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The Study of the 5-min Walking Accessibility for Pickup Points in Thessaloniki: Enhancing Logistics' Last Mile Sustainability

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Abstract. The UN World Health Organization deemed COVID-19 to be over as a public health emergency on May 5, 2023. Nonetheless, COVID-19 continues to impact every facet of human existence, encompassing urban planning. Today, e-commerce is a commonplace purchasing choice that has led to significant changes in city logistics, particularly in last-mile deliveries. Consequently, there is an increase in CO_2 levels and traffic congestion.

Therefore, there is need to analyse the existing and potential pick-up point networks, so to understand how easy it is for the user to pick up products and avoid home delivery. The present research focused in the central area of the city of Thessaloniki, Greece. The under-study area is characterised by the presence of many pick-up points which were identified with on-site surveys. Following the calculation of the 5-min walk isochrones, it was found that there are many (mainly) lockers. In addition, their location is mainly in the central area, while they also appear, but in reduced numbers, in the pericentre.

The evaluation of accessibility reveals that 50% of the residents in the central area resides within 5 min walking distance from a pick-up point while the respective percentage is about 25% of the residents when considering the pericentre.

The research findings can support the design of efficient strategies directed to the service management companies. The findings can also improve the customers' experience as far as online shopping is concerned by offering a better shopping experience, i.e., easiness to choose pick-up points, save on delivery etc.

Keyword: Last mile logistics · pickup point · 5-min walking isochrones · Thessaloniki metropolitan area

1 Introduction

E-commerce has experienced a strong growth in last years, especially after COVID-19 pandemic [1]. It has heavily modified the shape of last-mile logistics in urban area in last decades [2, 3]. Several consequences have arisen from that: fragmentation of deliveries,

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missed deliveries, returns, elements that contributed to negative externalities of last-mile logistics in urban environment [4].

A study conducted by [5] highlighted the preponderance of home deliveries with an increasing demand for fragmented and smaller goods.

At the same time during the various pandemic phases, e-commerce volumes increased, but unevenly according to the types of goods and with fluctuations during the various lockout periods.

A study conducted by [6] traced the evolution of the COVID-19 pandemic and logistics binomial from a spatial and temporal point of view, considering scientific articles published from 2000 to 2021, emphasising the need to adapt commercial activities to the changing situation by anticipating people's needs, creating e-commerce sites capable of accompanying customers during this delicate phase.

Pick-up points are useful tools that often e-commerce operators offer to customers. They serve role to aggregate deliveries in points (i.e. lockers or store), giving customers the opportunity to pick-up the parcel when needed. This may reduce negative externalities arising from missed deliveries; also, it can contribute in reduction of total km travelled by logistics vehicles [7].

Several criticalities emerge from pick-up points distribution. It has been evidenced how pick-up points are considered a viable alternative to traditional home delivery if the point is reachable in less than 5 min from customer's home [8]; it has been also highlighted that pick-up points are unsustainable if private cars are used as mode to reach them [9]. The combination of these two considerations lead to this initial result: pick-up points have to be reachable in 5 walking minutes to be considered a viable alternative and, at the same time, to be environmentally friendly.

The core study of pick-up points analysis has focused on accessibility of points network. Several studies [10–12] have highlighted that the population living in the five-minutes walking isochrone as a good indicator to consider the performance of a pick-up points network.

Starting from the highlighted research, the study aims to provide a general assessment on the diffusion of pick-up points in a local European reality. The study of the accessibility of the points allows, in fact, to define a first level of demand coverage and to study the penetration of this strategy. In particular, with the growth of e-commerce in many EU countries, driven by the COVID-19 pandemic [13], it has led to fragmentation of deliveries and an increase in vehicles linked to urban logistics [10, 14]. It is appropriate to consider that a high percentage of air pollution in urban areas derives from city logistics vehicles [15]; the reduction of total vehicle-km traveled is an objective to be pursued, also in light of the Sustainable Development Goals of Agenda 2030 [16]. More specifically, the reduction of carbon emissions is the core of Goal 13, "Climate action"; in the specific case, the interested target is 13.2, "Integrate climate change measures into national policies, strategies and planning". It has been determined that good location of pick-up points can lead to a reduction in the negative externalities of transport, if they are effectively distributed in such a way as to prevent the user from considering the car as an alternative to reach the point [17, 18]. In this context, it is useful to study the pedestrian accessibility of the points; this element, if appropriately studied, influences vehicular routing assumes a greater importance also in the definition of Sustainable

Urban Mobility Plans (SUMPs) and Sustainable Urban Logistics Plans (SULPs) [19, 20]. Analysis of location of pick-up points may help planners and companies to define better strategies to optimize vehicles routing, in order to reduce total vehicle-km traveled. This type of analysis also suggests a study on where logistics companies find it useful to position pick-up points; This analysis is also useful as a basis for the study of integrated on-demand mobility systems for passengers and goods (DRTL).

In this work, main goal is the analysis and characterization of a case study in mediterranean Europe. The study area proposed is Thessaloniki, Region of Central Macedonia (Greece).

Section 2 provides a description of the study area. Section 3 shows the methodology used in-depth. Section 4 describes the main results. Finally, results are described in Sect. 5, where main conclusions are also presented.

2 Background

E-commerce is an established yet evolving phenomenon, still growing steadily, so much so that it is one of the best-performing engines in the world economy. Concerning Greece, a recent report highlights the fact that the country "*can boost its digital macroeconomy by shifting its level of digital commerce maturity in the next three to five years*" [21]. Pick-up points are becoming the preferred delivery option, but many retailers still do not have this option for their customers.

Shoppers who spend a lot online are reassured by pick-up points. They reduce users' anxiety about having to stay at home to receive parcels and eliminate the stress of having to double-check whether they have agreed on a safe place with that particular courier. It is a fact: offering a pick-up point reduces the rate of shopping cart abandonment, particularly by shoppers with high-value baskets.

Pick-up points are in fact a free service and are used for the release and retrieval of goods ordered online. In many cases, they are also storage points for return items. Their main peculiarity is their location in busy or 'strategic' areas, combined with their accessibility at all (or nearly all) times. There are different types of pick-up points:

- smart lockers, i.e. self-service lockers that open by means of a code or scanning a QR code;
- commercial establishments (shops, tobacconists, bars, post offices…) participating for certain couriers or services;
- outlets of the same eCommerce brand.

Pick-up points are now a service offered by major retailers to increase online sales while making life easier for consumers.

The main advantage of a pick-up point and a smart parcel locker is the possibility to collect the parcel at a convenient time without having to entrust friends and relatives with this task. Moreover, since today no one can stay at home and wait for the courier, offering a pick-up point provides a flexible and convenient solution for those who like to shop online but have a hectic life.

Finally, picking up your parcel at a pick-up point increasingly means combining business and pleasure, as they are generally located in places with catering services or

shops, or it is an opportunity for a break at work, if your company has adopted a smart parcel locker service.

We can therefore say with certainty that being able to receive a purchase made online at a pick-up point or smart parcel locker means avoiding stocks and waiting for the courier at home.

There are, therefore, many advantages for both the sender and the recipient, advantages that respond to the ever-increasing spread of e-commerce sites and the constant growth of online shopping, especially during the festive period.

There is also a trend in recent years to install delivery lockers or smart parcel lockers, which more and more companies are making available to their employees as part of their corporate welfare policies and which are an increasingly popular benefit.

According to [22] the advantages of pick-up points for merchants can be summarized as follows:

- 100% successful delivery attempts;
- lower shipping costs, due to fewer courier trips;
- greater omnichannel integration, in the case of shipments to their own shops.

The benefits for eCommerce customers are numerous and significant:

- convenience;
- faster delivery;
- greater privacy;
- easier returns.

Another benefit, from which everyone benefits, is the decrease in CO_2 emissions, thanks to load-optimised deliveries and at night or less busy hours [23].

To increase the efficiency of last-mile delivery, online retailers can adopt pick-up points in their operations and the retailer can then incentivise customers to switch from home delivery to the pick-up point to reduce costs [24].

There are few quantitative publications on logistics distribution mode selection with logistics service providers as the main body and last-mile distribution time, price and mode selection from a strategic perspective [25].

A study conducted by [26] found a significant gap between the delivery options available on e-commerce websites and consumer preferences for last-mile delivery. In particular, it was emphasized that delivery time and accuracy are the biggest obstacles in the delivery chain, while highlighting the lack of home delivery services in the market.

In order to be able to better explore the concept of sustainability, it is considered appropriate to focus on the accessibility of these pick-up points on foot in order to further limit emissions and further reduce the use of private vehicles to reach them.

3 Study Area

The Thessaloniki Metropolitan Area includes the Municipalities of Thessaloniki, Kalamaria, Neapoli-Sykies, Pavlos Melas, Kordelio-Evosmos, Ampelokipoi-Menemeni and Pylaia-Hortiati, Themraikos, Thermis and Oraiokastro (see Fig. 1). The total population is over 1mo residents, and the area covers over 1,200 km^2.



Fig. 1. Thessaloniki Metropolitan Area map [27].

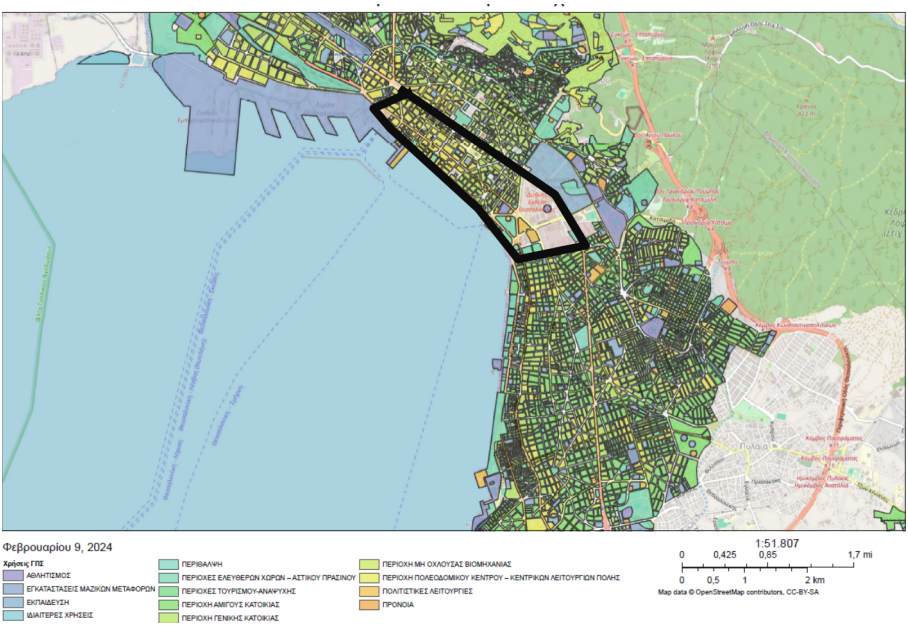

Fig. 2. Land uses map if the Municipality of Thessaloniki [34].

The Municipality of Thessaloniki is the most important administrative, cultural and business center in northern Greece, as well as the second largest city in Greece. There is a coastal line of over 50km length, with a newly constructed waterfront [28]. The Municipality covers almost 19km^2 [29] and its total population is almost 325,000 residents [30] and the population's density is 17,105 residents per km^2 [31]. The road network length is roughly estimated between 300km and 320km, while in the Regional Unit of Thessaloniki, there are almost 100,000 registered commercial vehicles (both public and private usage) [32]. As the city of Thessaloniki is the commercial center of the Regional Unit, it can be assumed that the majority of these commercial vehicles are mobilized inside the borders of the city. Although outdated, the distribution of the properties in relation to their usage in the Municipality during the period 2000–2007 was the following: 84% residential, 6% commercial, 9.6% services and 0.4% auxiliary [33].

Figure 2 presents the types of land uses of the Municipality of Thessaloniki [34]. The central area of the city (the area inside the black lines) is the historical and commercial area, in which many retail shops are located as well as services.

4 Methodology

Section 4 concerns the methodology developed aiming to study components of accessibility to a set of points in urban area, by taking into consideration among others elements of demand.

The elements required to study a pick-up points network are:

- Study area, characterized by a population POP divided into n = 1,2,…N zones, each of them characterized by a surface An and a population residing POP_n;
- Pick-up point set p = 1,2,…P. Each point has to be characterized by its position in the study area;
- A road network. Because of the topic of the work, great emphasis is on pedestrian roads;
- A quantitative parameter for defining the accessibility to pick-up points.

Pick-up points are elements of the supply system. Elements recalled are mainly linked to supply system (Pick-up points and road network), while Population is considered as the main demand-related variable. As a preliminary study, the use of aggregate value is considered satisfactory.

The last point is the criteria that allows the match between demand and the supply.

Recalling Cardenas [7] and Weltevreden [8], the criteria chosen is the walking accessibility to network in 5 min: more than 5 min could discourage the user from considering pick-up points as a viable alternative; the use of car, even if 5 min, is not considered a viable alternative for sustainability reasons.

Consider i_p as the isochrone generated in a 5-min walking from point p. Being I_p the area that falls inside the isochrone i_p, there is the need to evaluate the population living inside Ip, POP_p. Population is often linked to the characteristics of data available; in this case, we are considering a common case, in which population POP_n is known for each zone n. Another assumption is POP_n uniformly distributed into zone n, characterized by surface A_n; this is possible due to the nature of data. Population data are often divided by census area, maximizing the homogeneity of urban and environmental characteristics.

Considering these assumptions, it is possible to define the population living inside the area $A_{n,p}$, intersection between A_p and I_p, as

$$POP_{n,p} = \frac{A_{n,p}}{A_n} POP_n \tag{3.1}$$

Given all these elements, the population living in the area I_p is given by

$$POP_p = \sum_{n=1}^{N} POP_{n,p} \tag{3.2}$$

This value represents the population living in a generic area. Aiming to represent an absolute value, it is possible to evaluate the share of population living in I_p as

$$POP_{p,\%} = \frac{POP_p}{POP} \tag{3.3}$$

It is more useful to consider this parameter given the entire system. Also, as suggested in Sect. 2, often pick-up points catching area overlaps, making necessary to study the union of areas instead of considering them separately. It is possible to define the global 5-min catching area I_{TOT} as

$$I_{TOT} = \bigcup_{p=1}^{P} I_p \tag{3.4}$$

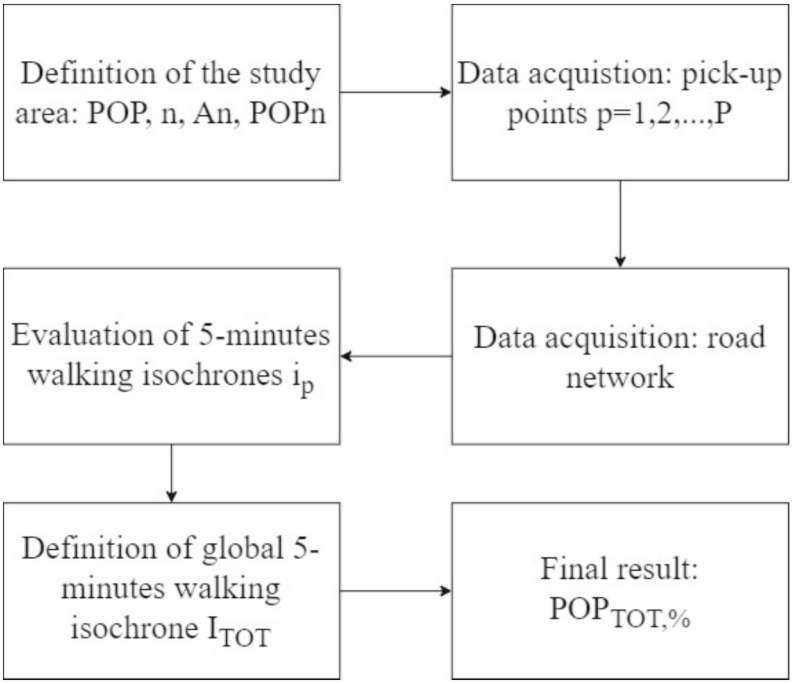

Fig. 3. Methodological steps

Equation (3.2) may be applied to I_{TOT}. Finally, considering the extension of Eq. (3.3) to I_{TOT}, it is possible to evaluate the value of $POP_{TOT,\%}$, the indicator who estimates the number of people who live in 5 min or less walk from nearest pick-up point in the study area.

$$POP_{TOT,\%} = \frac{POP_{TOT}}{POP} \tag{3.5}$$

The methodology discussed is schematically summarized in Fig. 3.

5 Results

The under-study area is described in Sect. 3 study and the operator considered for the study is Skroutz [35], the main e-commerce operator in Greece, having and operating a large network of pick-up points. For the case study under consideration, two kinds of points are considered:

- Points that fall inside the defined study area;
- Points that fall outside the defined study area but placed next to its boundaries.

This assumption is needed to better define the user perspective: people, even if living inside the study area, may consider the possibility to use a pick-up point placed outside the area, if it is very near. Due to the continuity of urban environment, especially in the Northern and South-Eastern side of the city, between Thessaloniki and neighboring municipalities, this approach allows a better approximation (Fig. 4).

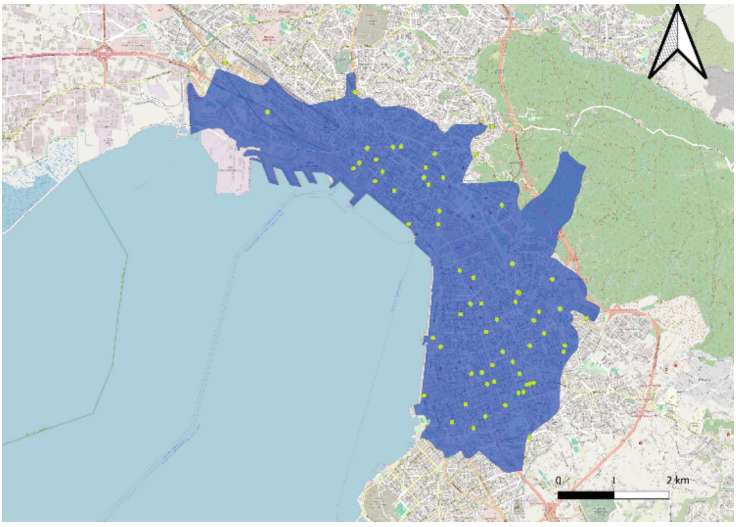

Fig. 4. Pick-up points considered (Source: authors' elaboration based on QGis [36] and Openstreetmap [37])

The points considered are in total 65, 60 of which are placed in Thessaloniki Municipality. The remaining 5 are placed in the Municipalities of Ampelokipoi – Menemeni, Neapoli – Sykies and Pylea – Chortiatis. The geographic distribution of points is shown in Fig. 5.

The evaluation of I_{TOT} is done. It is shown in Fig. 5.

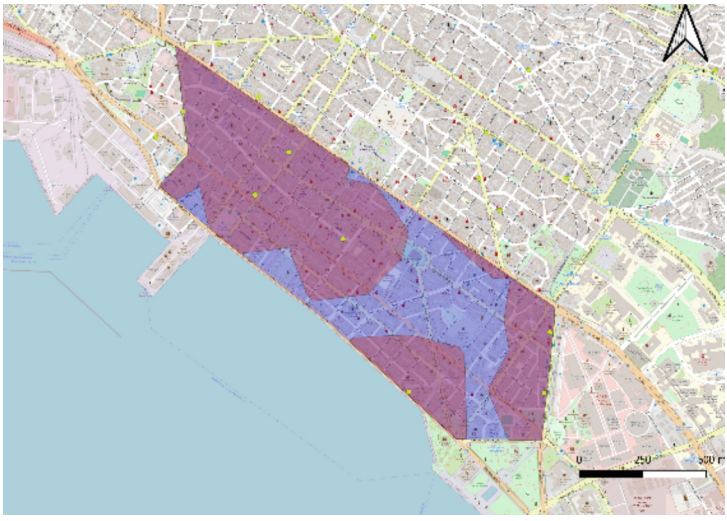

Fig. 6. Isochrone I_{TOT} for the Aggelaki-Egnatia-Dodekanisou-(Leoforos) Nikis Avenue area (Source: authors' elaboration based on QGis [28] and Openstreetmap [29])

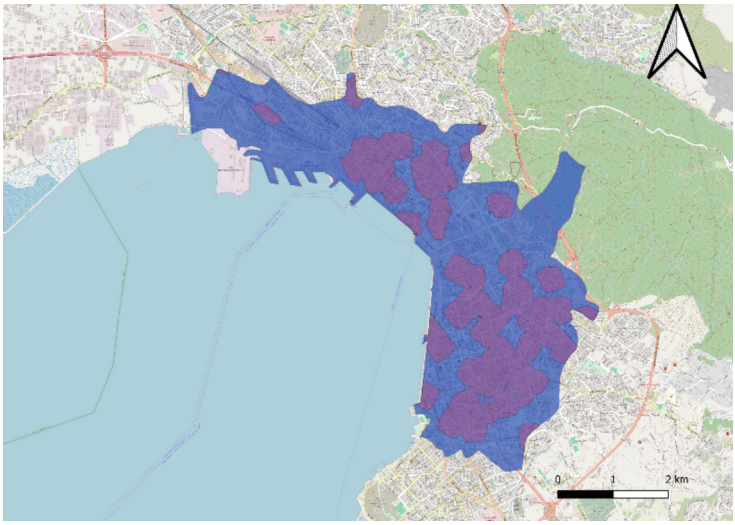

Fig. 5. Isochrone I_{TOT} for the study area (Source: authors' elaboration based on QGIS [36] and Openstreetmap [37])

Globally, the population covered by 5-min walking isochrone is 39,7% of the total. Within the basin considered, and once the criteria for choosing services have been identified, the operators who manage sea transport services are defined in Tab. X.

It is possible to see some inhomogeneities between different zones. Central area ("the body of butterfly") and South-Western area are generally well-covered. In Fig. 6 is proposed a focus on the Aggelaki-Egnatia-Dodekanisou-(Leoforos) Nikis Avenue.

In this case, the evaluation of population coverage is near to 70%, showing a value much higher than the global one.

6 Discussion and Conclusion

Different considerations are necessary. E-commerce has seen a great growth in last decades; even less developed regions, in the Western European context, like Greece or Southern Italy, have to deal with it. Traditional retail is not disappearing but has to coexists with e-commerce. Pick-up point is a tool that often explains how these two channels may coexists: several times, a retail store also offers the possibility to host a pick-up point for a national-scale logistics company. Also, it is important to recall that pick-up points may have in a sustainable logistics perspective; concentration of deliveries may lead to a reduction in emissions, but only if it is coupled with an improving in walking mobility.

The work illustrates a methodology for the evaluation of pick-up point accessibility, but also highlights the application of an interesting case study. Municipalities of Thessaloniki is the second Greek city by population, and it has several criticalities both from logistics and mobility point of view. Also, it is a big urban reality in a country mainly rural, with an economic development similar to several case studies analysed in other works [38].

Results showed a great distribution of pick-up points in the area considered, showing how this strategy is considered as important not only for international operators (like Amazon) but also for national scale operators (Skroutz). The population coverage is good, even if it is not equally distributed; as seen in previous sections, some parts of the city are characterized by clusters of points; in others, however, there is not a single pick-up point. The analysis has focused of the main central area of the Thessaloniki municipality, that showed a great coverage. The results highlight that pick-up point are a channel common in the city, but with several limits that have been experienced in other context. Mainly, the uneven distribution of points and the trend to form cluster confirms results from other cities. Points are mainly located in central area of the city; these points are mainly at the service of pedestrian mobility for the collection of parcels from users. However, some points are located in peripheral areas, close to main road axes of regional importance; this represents a first basis on which to develop subsequent analyzes for the feasibility of DRTL-type services [39, 40]. Among the future developments of the research, we intend to verify the feasibility of DRTL-type services that allow the parcel delivery service to be integrated starting from these peripheral points with passenger transport services to reach the main city center [41, 42]. These results allow another consideration: differences in distribution could reflect differences in accessibility to network, indicating variability in possibilities from people on the basis of place of residence. These aspects, that could led to more considerations on exclusion from logistics services, has to be further analyzed in future developments.

The main limitation of the study is related to the demand aspects. The only parameter considered is the population; this is useful for doing a preliminary study, but a focus on specific e-commerce users' categories is among the future developments of the research; knowing the demand generated for e-commerce in each zone of the city, it is possible to better understand the efficacy of pick-up points distribution, evaluated not in terms of population covered but in terms of e-commerce demand covered. Population is an indicator of potential demand that may be refined.

Also, the study may be extended to other municipalities of Thessaloniki greater area and of smaller cities and towns of Greece; this may be very interesting to see if the results for Thessaloniki are confirmed in smaller realities or if they are specific to its urban dimension.

Current work may be useful for several categories of stakeholders. Mainly, logistics operators in Greece and other European countries are interested; in this work, they can read a preliminary approach to analyze their system considering basic elements of demand. Public authorities are interested in this work too, to have a tool to evaluate quantitative elements that are not often considered in transportation planning.

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Investigating Commercial Vehicles' Parking Habits in Urban Areas: The Case of Thessaloniki, Greece

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Abstract. The COVID-19 pandemic changed the way modern societies are organized and perform in so many ways. Inevitably, Urban Road Freight Transport (URFT) has also been affected by the pandemic in many ways. For example, e-commerce has increased over the last 3 years compared to the traditional shopping ways that required the physical presence of the buyers at the retail shops; last mile delivery has changed due to the necessity of mobilizing environmentally friendly vehicles and abandoning gradually vehicles with internal combustion engines, etc. Despite the above, URFT still requires specially designed areas and facilities for its activities to be undertaken. Such areas are the parking spaces dedicated to be used only by commercial vehicles (VCs) in order to perform loading and unloading activities. This necessity seems not only to be constant but also to be on the increase. At the city of Thessaloniki, Greece, our research team has, over the last 14 years, been periodically monitoring these parking spaces in terms of their evolution concerning their number and location as well as their level of usage. The present paper presents the evolution of the number, location, and level of usage of the abovementioned parking spaces to become a useful tool for the local decision-makers (municipal authorities). The issue of determining the locations of these loading and unloading parking spaces for commercial vehicles must be based on scientific data and the true needs of the URFT's stakeholders. After all, public space in urban areas decreases year after year. It is important and almost self-evident that the way the available public space is used should maximize society's benefit. In this framework, the current paper presents the key findings of this evolution in the city of Thessaloniki, enumerating proposals on how to achieve maximum usage of the parking spaces without affecting the URFT's level of performance.

Keyword: Parking spaces for commercial vehicles · Logistics · Thessaloniki

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1 Introduction

The COVID-19 pandemic affected the life of all societies for almost 3 years in many ways. Central governments worldwide applied mobility restriction measures, lockdowns, teleworking and many other measures to minimize the effects.

Inevitably, Urban Road Freight Transport (URFT) was also affected by the pandemic in many ways. During the lockdowns and mobility restrictions measures, e-commerce increased as people had to find ways to continue their lives without being able to continue shopping with the traditional way: with physical presence at the retail shops. Last mile delivery also changed as the demand was decreased and delivering goods required a non-touching process due to health protocols. Even when the pandemic was set under partial control at least at the more advanced societies, the necessity of mobilizing environmentally friendly vehicles and abandoning gradually vehicles with internal combustion engines was brought to the surface. Despite all the above-mentioned, URFT still requires specially designed areas and facilities in order for its activities to be undertaken, dedicated for this purpose parking spaces. This necessity is constant and perhaps now is increasing as urban mobility is not achieved.

At the city of Thessaloniki, Greece, the authors have been (over the last 14 years) periodically monitoring these parking spaces in terms of their evolution (i.e. number, locations and level of usage). The paper presents this evolution aiming to become a useful tool at the hands of the local decision-makers (municipal authorities). The issue of determining the number and the locations of these parking spaces must be based on scientific data and the true needs of the URFT's stakeholders. After all, available space in urban areas becomes more and more difficult to be found, making harder and harder for the local and regional policy makers to decide how to use it. It is important and almost self-evident that the available public space must be used in such way that maximizes society's benefit.

In this framework, the paper also presents the key findings of this evolution in the city of Thessaloniki, enumerating proposals on how to achieve maximum usage of the parking spaces without affecting the URFT's level of performance by Pitsiava-Latinopoulou et al. [1]. The paper is structured as the following: Sect. 2 presents the Literature Review, Sect. 3 present the Methodology followed for the data collection, Sect. 4 presents the Analysis and results and finally Sect. 5 the main Conclusions.

2 Literature Review

A significant number of case studies research private cars parking problems in urban areas by Abbood et al. [2], Andreeva and Muzykin [3], Magdin et al. [4], Cempirek et al. [5], Shen et al. [6], Holguin-Veras and Amaya [7], Jacob and Menedez [8] while other are focused on the commercial vehicles' (CVs) parking problems as Vorhes et al. [9], Kawamura et al. [10], Jaller and Holguin-Veras [11], Kim and Wang [12], Tamayo et al. [13], de Oliveira and Guerra [14], Wenneman et al. [15], Betkier and Macioszek [16] and finally Giraldo et al. [17].

As mentioned above, as urban areas become denser, available land for parking decreases, making it increasingly difficult for CVs to find a parking spot. Additionally, the high cost of land in urban areas makes it economically unfeasible to construct new parking spaces to cover the carriers' needs.

Another challenge is the limited time CVs are permitted to park in certain areas. During this time window, loading/unloading activities must be implemented making it difficult for the drivers to complete their tasks efficiently as mentioned by Figliozzi [18] and Pinto et al. [19]. This limitation can result in drivers spending more time searching for parking spots than completing their tasks.

The lack of available parking spaces and time limitations can lead to increased traffic congestion, fuel consumption, and emissions. Furthermore, low hourly occupancy of these parking spaces by the CVs' drivers in some cases is explained by the fact that they prefer to park illegally as closer as they can to their final destination than to these specially constructed parking places as mentioned by Lizbetin and Bartuska [20] and Bouhouras et al. [21] creating thus bottle-necks and congestion phenomena, especially when more than one CVs approach simultaneously the same parking space as mentioned by Chiara and Cheach [22] and Ezquerro et al. [23] Parking choices and decision making criteria of the CVs' drivers as well as other issues have been examined by many researchers: ways to improve mobility through the optimization of of loading/ unloading bays' usage by Alho et al. [24]; identifying the impact of traffic congestion when optimizing delivery routes in real time by Alvarez et al. [25]; planning the on-street loading/ unloading spaces by Aiura and Taniguchi [26]; analyzing available space proper usage concerning delivery practices by Gardrat and Serouge [27].

3 Methodology

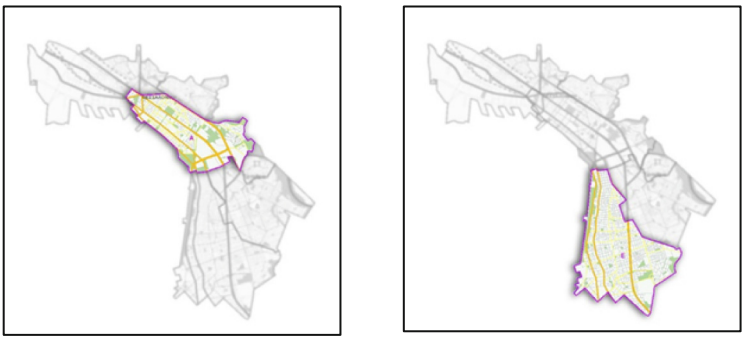
The under-study area concerns the Municipality of Thessaloniki, covering almost 19km^2 according to Municipality of Thessaloniki [28] and specifically a) city's commercial central area/Municipal Community A and b) the eastern area/Municipal Community E as presented in Fig. 1 according to Municipality of Thessaloniki [29].

Since 2007, the authors have been monitoring periodically (nonconsecutive timeline) URFT system in the city of Thessaloniki, collecting data about geographical position (coordinates) and the number of the above-described dedicated CVs' parking spaces.

The present paper presents in a summarized way the main findings of our research over the last 14 years. Through in situ surveys, the undergraduate students (research teams) of School of Rural & Surveying Engineering of the Aristotle University of Thessaloniki in the framework of their Thesis recorded the geographical locations of these parking spaces using mobile GPS devices (after 2014) as well their number and relative parking legislation by Adamou and Oulis [30], Zimis and Lamprou [31], Kakarakis et al. [32], Giannoudis and Emmanouilidis [33], Danelatos and Tsakiris [34] and Koenta [35].

The research teams walked along the entire road network of these two areas to identify by the vertical and horizontal respective signage the CVs' parking spaces.

This process was time consuming and, in some cases, the crews faced tough weather conditions (rain, snowfall, strong wind). Because the research teams were using mobile GPS devices provided by the Laboratory of Transportation Planning, Traffic & Highway



(a) (b)

Fig. 1. (a) Municipal Community A; (b) Municipal Community E of the city of Thessaloniki (Municipality of Thessaloniki, 2022)

Engineering the precision on the parking spaces location is ±2m. To minimize the deviation, the research teams in the field measured the distance of the parking spaces' borders from permanently established elements of the sidewalks (e.g. streetlights and/ or neighboring buildings).

Moreover, the research teams recorded where possible ancillary data such as the status of these parking spaces (free, occupied by CVs, occupied by other type of vehicles, occupied by other items such as trashcans).

When this process was completed and the respective database was developed, the research teams returned to the field to record data at predefined parking spaces concerning their hourly occupancy by CVs (the number of CVs using the parking space for loading/unloading procedures during the period of one hour).

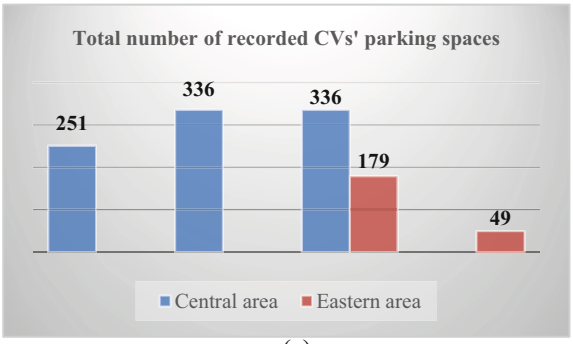
It must be mentioned that the research teams were advised to also collect data concerning CVs illegally parked (a distance smaller than 20 m from the parking space being surveyed) to perform loading/ unloading activities.

4 Analysis and Results

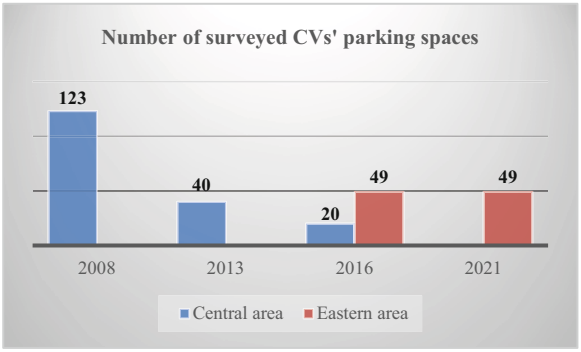
Based on the data presented in Fig. 2(a) and 2(b), the number of CVs' recorded parking spaces over exceeded the number of the surveyors. As a result, it was not possible to conduct simultaneous surveys for all these parking spaces.

Therefore, the surveys were spread over time covering each time a single 'time frame' of the (at the time) current situation. When all surveys concerning hourly occupation were completed, the collected data were analyzed as presented in Fig. 2(c).

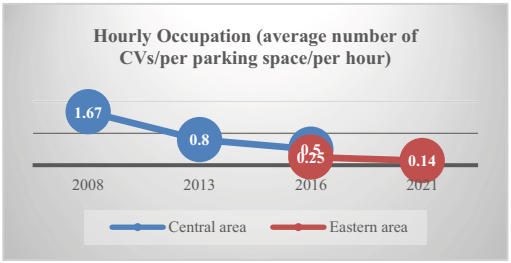
During the surveys in 2014, the surveyed CV's parking spaces (40 in number) were located at the central area. Most of these surveys concerned illegally occupied parking spaces mainly by private cars and in a few cases by trashcans [32]. During the surveys in 2017 in the eastern area, 58 loading/ unloading activities were recorded in total. By those, 43 (74%) concerned CVs parking illegally while the rest 15 (26%) concerned CVs using legally the parking spaces [34].



(a)



(b)



(c)

Fig. 2. (a)Total number of recorded CVs' parking spaces; (b) Number of surveyed CVs' parking spaces; (c) Hourly Occupation (Own elaboration)

Regarding the central area during the 2017 surveys, 98 loading/ unloading activities were recorded in total. By those, 83 (85%) concerned parking illegally while the rest 15 (15%) concerned CVs legally using the parking spaces [34].

Finally, during the 2022 surveys in the eastern area, 11 loading/ unloading activities were recorded. Five of them (45%) concerned illegal parking, while the rest six (54%) concerned legally parking CVs [35]. Although in many cases CVPS were occupied by private cars or trashcans, not allowing thus the drivers of the CVs to use them, the drivers

chose not to search for the next closer to them available parking space, but instead they decided to park illegally to load/ unload the commodities/ goods.

The above-mentioned collected and analysed data are presented in Figs. 3, 4, 5, 6 and 7. Specifically, Fig. 3 presents the evolution of the available CVPS between 2008 and 2016 as recorded in three periods (2008, 2013 and 2016) in the central area of the Municipality of Thessaloniki. The number of CVPS between 2013 and 2016 remained the same but their locations were different.



Fig. 3. Recorded available CVPS in the central area of the Municipality of Thessaloniki for the years 2008, 2013 and 2016

Figure 4 presents the evolution of the available CVPS between 2016 and 2021 as recorded in two period (2016 and 2021). The total number of the available CVPS in this area was slightly increased; the locations of just few of them were different between the surveys.

Regarding the surveyed level of usage of the CVPS located in the two above-mentioned areas, Figs. 5, 6 and 7 present (as heat maps) the hourly occupancy (number of CVs using the CVPS during a period of one hour) of the CVPS in order to implement loading/ unloading procedures for the following cases a) the central area for the year 2016, b) the eastern area for the year 2016 and c) the eastern area for the year 2021.

Based on Fig. 5, the higher number of CVs using a CVPS during an hour is three (3). That means that in average the crew of each CV required 20 min to implement their loading/ unloading procedures. Furthermore, the locations with the higher occupancy are located at the core of the commercial center of the city (the area enclosed by Tsimiski str., Leoforos Egnatia, Dodekanisou str. And Aggelaki str.). In this area, most of the retail shops are located as well as residents and of course other types of land uses. Tsimiski str. as well as Leoforos Egnatia serve in a daily basis significant traffic volume. Tsimiski str. is a one-way road heading from East to West with three (3) lanes for the general traffic as well as one (1) bus lane. Leoforos Egnatia, is a two-way road with two (2) lanes per



Fig. 4. Recorded available CVPS in the eastern area of the Municipality of Thessaloniki for the years 2016 and 2022

direction for the general traffic as well as one bus lane. Finally, Figs. 6 and 7 present the hourly occupation of the CVPS at the eastern area for the years 2016 and 2021.



Fig. 5. Recorded hourly occupancy at the CVPS in the central area of the Municipality of Thessaloniki for the year 2016



Fig. 6. Recorded hourly occupancy at the CVPS in the eastern area of the Municipality of Thessaloniki for the year 2016



Fig. 7. Recorded hourly occupancy at the CVPS in the eastern area of the Municipality of Thessaloniki for the year 2021

By analysing Figs. 6 and 7 during this period of 5 years, the hourly occupancy presenting high values remained only for one area (1), as area (2) disappeared. Furthermore, low hourly occupancy values were recorded in three (3) new area in 2021 compared to 2016 near the coastal zone and along Vas. Olgas str. The remaining high hourly occupancy value concerns the intersection of 25 Martiou and Delfon streets. Many retail shops are installed along those two streets that serve significant traffic volumes on a daily basis.

5 Conclusions

There are some quite interesting conclusions extracted from this paper, despite the limitations acknowledged. The main limitation concerns the fact that during the surveys, the number of surveyors was not sufficient to collect data simultaneously regarding hourly occupancy from all surveyed CVPS. That means that the surveyors were able to collect data from a specific number of CVPS per day, recording just a frame of how the URTF system performed each day. The second significant restriction concerns the fact that the timeline of the surveys is fragmentary and not consecutive. This is because the surveys were implemented by (at the time) undergraduate students at School of Rural and Surveying Engineering of the Aristotle University of Thessaloniki in the framework of their Theses.

In the central area, despite the increase of the available CVPS between 2008 and 2016 (33.9%), the hourly occupancy has been decreasing and specifically between 2008 and 2013 has decreased by 97%. In the eastern area, based on the identified CVPS (without calculating the assumed CVPS) there was an increase on their number between 2016 and 2022 (32.4%) but the hourly occupancy was decreased by 44%. Researchers suggest that low values of hourly occupancy seem to be a common problem in urban areas according to de Oliveira & Guerra (2014), while others highlight the fact that in several cases the drivers of CVs prefer to park illegally close to their final destination rather than use a CVPS even if it rather close to that location (not over 50 m) [23]. It can be strongly assumed (based on the collected and analysed data) that the URFT system in the Municipality of Thessaloniki is underperforming. Furthermore, it is rather obvious that the network of CVPS is not properly designed in terms of their numbers and locations. Despite increasing their numbers, hourly occupancy is decreasing meaning that the CVs park illegally rather than suing them to perform loading/ unloading procedures. Another interesting aspect (remains though to be thoroughly analysed by the authors) concerns if and in which level the Municipal Police supervises the CVPS ensuring that they are free and properly used by the CVs. The Municipal Police is assigned to supervise not only traffic and parking but many other aspects of the city's life, with a restricted number of personnel.

Innovative solutions could be applied concerning monitoring the CVPS by using sensors installed at them which inform the respective authorities about a) which CVPS are occupied, b) for how long and c) by which vehicles (the registration plate of the vehicle is scanned). Through this approach, Municipal Police will not be forced to supervise the CVPS in situ. Another measure, could consider the installation of an Urban Consolidation Centre serving the under-study area with Light Goods Vehicles (LGVs) instead of Medium and Heavy Goods Vehicles (MGVs/ HGVs) [36]. Although this would require a higher number of trips to serve the needs of the receivers (as the loading capacity of LGVs is smaller than MGVs and HGVs) which could lead to higher air pollution as higher number of vehicles should be mobilized, new technologies as well as alternative types of vehicles (tricycles, bicycles, electric vehicles) could perform as counterweight.

It is necessary for the respective authorities to develop a holistic approach not only for CVPS' network and their level of usage, but the way the URFT system in the city of Thessaloniki is designed and performing. It is important to monitor (with the highest

possible frequency) the aspects presented in this paper, so that any decision made is based on scientific data covering the real and true needs of the URFT system's stakeholders.

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Analysis of e-scooter Users' Riding Behaviour at Signalized Junctions

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Abstract. During the last few years, micromobility services have blossomed globally. Shared e-scooters are the main microbility mode that have become rapidly a fashionable trend. Yet, this rapid spread also made obvious that urban areas were not adequately prepared for integrating micromobility in their transportation systems. Many issues appeared related with invasion of public space, vandalism of e-scooters, and concerns of road safety. Currently, most countries have already established operating guidelines about micromobility, while some others are in the process of doing so. For establishing appropriate guidelines, or for modifying them based on the actual needs, it is important to constantly monitor micromobility operations and investigate those issues that were mostly influenced by micromobility. This paper aims to shed some light on the riding behaviour of e-scooter users by analyzing their actions at signalized junctions. Observations of 330 e-scooter users were collected at 12 signalized junctions in the city of Thessaloniki, Greece. More specifically, the decision of e-scooter users to cross illegally during the red-light phase or to stop appropriately was observed, as well as the speed difference before and after the change of the traffic signal from green to yellow. Additionally, the geometry and functional characteristics of the junctions were collected as well as user-related attributes. The statistical analysis of the observations aims to identify how the two main variables that express the behaviour of e-scooter users (i.e., decision to cross illegally and speed difference) are affected either by the characteristics of the junctions or by the attributes of users.

Keywords: e-scooters · micromobility · signalized junctions

1 Introduction

E-scooters represent a recent addition to urban transportation systems, and their immediate impact has been noticeable. They have rapidly gained popularity, evidenced by the widespread adoption of shared services worldwide and the significant expansion of their market size. By the close of 2019, shared e-scooter services were available in

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over 220 cities across the United States and Europe, indicating their rapid spread [1]. Additionally, apart from shared e-scooters, there has been an increasing demand for private e-scooters. Private e-scooters dominated the industry in 2022, accounting for nearly 70% of the overall revenue. In summary, the global electric scooter market was valued at $33.18 billion USD in 2022 and is projected to grow at a rate of 9.9% from 2023 to 2030 according to Grand View Research [2].

Previous research suggests that e-scooters can contribute to addressing environmental concerns in cities by reducing air pollution [3]. Moreover, e-scooters are acknowledged as a mode that can serve short trips in a convenient and fast way [4]. Except of short distance trips, e-scooters and especially the shared ones, are considered a mean for improving intermodality through combining its use with public transport services [5, 6].

Concurrently, other studies emphasize the importance of mitigating inequalities in transportation access, promoting cost-saving measures, and enhancing mobility resilience [7, 8]. Numerous studies have explored public attitudes toward e-scooters, particularly among non-users, underscoring significant challenges such as inadequate infrastructure and the absence of a regulatory framework [9, 10]. According to a very recent study, users are eagerly anticipating new laws regulating the usage of e-scooters, such as optimizing speed limits, designating the usage of e-scooter infrastructure, and appointing dedicated parking places [11]. Indeed, appropriate regulatory frameworks seem to be essential for efficiently integrating e-scooters in modern transportation systems and gathering their full potential. As Felix et al. state, e-scooters generate several benefits, however these benefits are highly overshadowed by safety-related issues (almost €6M in annual costs) [12].

Considering the abovementioned issues that are related with the rapid spread of e-scooters, many countries have developed regulations. A report released by The Forum of European Road Safety Research Institutes conducted a comparative analysis across 18 European countries concerning e-scooters, with the goal of delineating disparities in their legal status and safety considerations [13]. As it can be seen in Fig. 1, the majority of the countries regard e-scooters as equivalent to bicycles. In the Czech Republic, scooters are categorized similarly to e-bikes. In several nations, classification is contingent upon speed or maximum power. For instance, in Finland, a scooter is treated as a pedestrian if its speed does not exceed 15 km/h; otherwise, it is classified as a bicycle. About half of the analyzed countries impose an age restriction, in numerous European countries, e-scooters can only be operated by individuals over 14 years old, with mandatory helmet use for those under 18. E-scooters are typically required to be ridden on cycle paths in nearly all countries, where available. In instances where cycle paths are unavailable, they are expected to be used on the road in Austria, France (if the speed limit is not higher than 50 km/h), Germany, Portugal, Sweden, and Switzerland. In Italy, users are permitted to utilize both cycle lanes and roads within areas with a speed limit of 30 km/h.

Interestingly, Germany is the only country where e-scooters are required to have a license plate. Across nearly all countries, the improper parking of e-scooters in public spaces is perceived as a safety concern for pedestrians, the elderly, the visually impaired,

and individuals with disabilities. Despite the significant potential of e-scooters as a transportation solution, particularly in densely populated cities with growing traffic congestion, various legislative challenges must be addressed. Addressing these issues would ensure that e-scooters are not only fast and flexible but also safe [14].

For efficiently addressing legislative challenges, more evidence is needed regarding how e-scooters are being used. It is commonly accepted that the riding behaviour of e-scooter users is inadequately studied. Aiming to contribute in filling this gap, this paper analyzes the behaviour of e-scooter users, specifically when approaching a signalized intersection. It is anticipated that the results of the paper will assist in guiding decision-makers in identifying measures and policies that will promote micromobility safety.

2 Methodology

2.1 Study Area

The study area encompasses the Municipality of Thessaloniki, situated within the Region of Central Macedonia in Northern Greece. The Municipality of Thessaloniki is home to approximately 320,000 inhabitants, making it the second most populous city in Greece. It is renowned as a major educational hub, Thessaloniki hosts four universities, with the Aristotle University of Thessaloniki accommodating around 75,000 registered students and 2,000 academic staff members. Thessaloniki faces traffic congestion issues stemming from heavy reliance on private vehicles and inadequate public transportation services. According to the Thessaloniki Sustainable Urban Mobility Plan [15], private cars account for 41.3% of trips, while public transport and motorcycles represent 33.7% and 11% modal share, respectively. Active modes of transportation, such as walking and cycling, constitute only a small percentage of modal share, at 9.2% and 1.7%, respectively [15].

Thessaloniki has limited bicycle culture and low cycling volumes. The city's bicycle network suffers from fragmentation, indirect routes, and safety concerns. The bicycle lane network is only of 12 km length, while the Municipality covers an area of 19.307 km^2. Prior to the introduction of shared e-scooter systems, Thessaloniki's residents had limited experience with shared mobility services. The city's only existing



Fig. 1. Elements of countries' regulatory frameworks for e-scooters usage [13].

shared mobility option was a dock-based bike-sharing system established in 2013. However, due to the scarcity of docking stations, this system failed to attract many users. Lime introduced a dockless shared e-scooter system in 2018, offering electric-powered scooters that could be parked anywhere. This innovative approach quickly intrigued Thessaloniki's residents, resulting in 850,000 trips within the first year. Following Lime's success, other providers like Hive and Rise entered the market.

All shared e-scooter systems operated without docks within a predefined geofenced area covering Thessaloniki Municipality and surrounding areas, determined by the companies without local authority consultation. Companies regularly redistributed their scooters throughout the day to balance supply and demand and ensure all vehicles were adequately charged.

The initial success of these systems prompted discussions about their benefits and challenges. Local authorities are now considering establishing docking stations to address issues of indiscriminate parking. However, there has been a decline in shared e-scooter usage over time. Factors contributing to this decline include high costs compared to other alternatives like public transport and walking, safety concerns due to inadequate cycling infrastructure, reduced interest following the initial curiosity, and the purchase of personal e-scooters by those recognizing their benefits.

The present paper specifically focuses on 12 signalized junctions, all of them located within the borders of the Municipality of Thessaloniki. The signalized junctions are located along 4 main road-axes of the city, which serve high traffic volumes and have a bicycle lane. Moreover, some of the signalized intersections were located in a close distance from the campuses of city's main universities. The existence of bicycle lane and the close distance from the universities were two criteria that were significantly considered for selecting locations where it would be more likely to have relatively high flows of e-scooters. The 4 selected road-axes are the following:

- Leoforos Nikis (Fig. 2a)
- Konstantinou Karamanli (Fig. 2b)
- Agiou Dimitriou (Fig. 2c)
- Leoforos Stratou (Fig. 2d).

2.2 Data Collection

As a first step, basic geometric and operational attributes were measured in the 12 signalized junctions. A summary of the measured elements is presented in Table 1.

It should be noted that for sequential junctions in the same road-axis, the traffic flow was measured once and it was assumed that the number of vehicles that enters the road-axis in one junction is approximately the same with the number of vehicles that exits the road-axis in the same junction. In the case of Konstantinou Karamanli, junctions 2.1–2.3 were covered with a single set of traffic flow measurements, while a different set of measurements were required for junctions 2.4–2.5, since these two junctions are not sequential with the previous three and the aforementioned assumption would not be plausible. It should be also noted that the traffic flow measurements, as well as the traffic signal measurements were conducted in peak-hours.

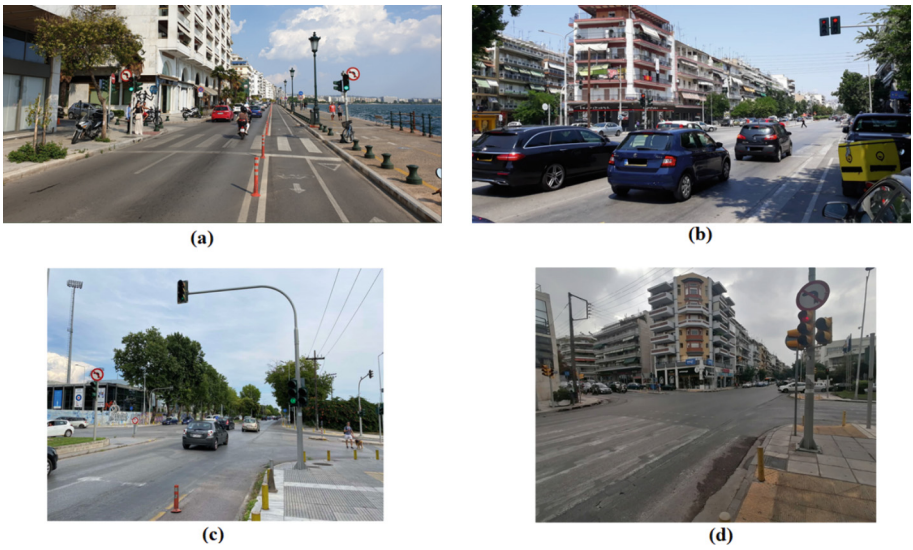

Fig. 2. Images from selected junctions in each of the four road-axes.

Table 1. Basic geometric and operational attributes of the signalized junctions.

Road axis	Junction id	Main road width (m)	Green light phase for main road (sec)	Red light phase for main rad (sec)	Hourly traffic flow in main road (PCU)
Leoforos Nikis	1.1	7	78	19	1824
	1.2	7	78	19	1824
	1.3	7	78	19	1824
Konstantinou Karamanli	2.1	12	57	30	1759
	2.2	12	36	51	1759
	2.3	12	39	48	1759
	2.4	7	49	38	1767
	2.5	10	35	52	1767
Agiou Dimitriou	3.1	10	22	65	1123
	3.2	7	41	56	1123
Leoforos Stratou	4.1	7	46	41	1653
	4.2	6	31	50	1653

The measurements were followed by the formation of a template for the observations. The elements that were included in this template are the following:

- Date/hour
- Gender of the e-scooter user
- Age class (only three wide classes were defined, i.e., < 20, 20–39, > 39, for reducing the possibilities for inaccurate estimations from the observers)
- If there was any source of distraction or not
- Distance of the e-scooter user from the traffic signal at the time that the green light phase was ending (the distance was estimated by initially marking users position in an appropriate drawing and then measuring the distance of this position from the traffic signal)
- Speed of the e-scooter user while the green light phase applies (the speed measurements were made through a handheld speed gun, model LTI 20/20 TruSpeed S)
- Speed of the e-scooter user three seconds after the ending of the green light phase (i.e. when the yellow light phase was shifting to the red one)
- If the user was wearing a safety helmet or not
- If there was at least one pedestrian waiting to cross the road
- If the e-scooter user crossed illegally the road (during the red light phase) or if he/she stopped appropriately.

As it becomes understood from the above description of the elements that were measured, for having a successful observation it was required to capture the e-scooter user at the moment that there was a change in the indication of the traffic light. For instance, e-scooter users that were identified during the green light phase and crossed the intersection without facing a change in the indication of the traffic light phase were not eligible for being observed.

Considering the exclusion of the abovementioned cases and also the low volumes of e-scooters in the city, the collection of a sufficient sample was really challenging. Finally, 331 valid observations were made and used for the analysis. The observations took place during two phases, i.e. October and November 2021 and from Mach to May 2022. The winter season was not utilized for observations, since the micromobility traffic drops significantly in the city. All observations were conducted under fine weather conditions.

In both phases the observations were undertaken by a couple of observers. The one observer was responsible for measuring the speeds before and after the change of the traffic light indication, while the second observer was responsible for observing all other elements and taking notes to the template. All observers initially participated in pilot observations for realizing how the tasks should be handled on site, for gaining familiarity with the handheld speed gun and for identifying the optimal spots where they should stand in each examined junction.

3 Results

The data selected through the observations are initially analyzed descriptively for providing an overview of the sample and the measured elements. Table 2 provides an overview for basic categorical variables of the analysis. It seems that most of the observed e-scooter riders are males. This indicates that e-scooters in Thessaloniki are mostly used

by males. This finding for Thessaloniki was also identified by a previous extensive survey [8] and it also agrees with findings for many other contexts [16–18]. A significant 12.7% had some audio or visual distraction while riding an e-scooter and approaching the signalized junction, while only the 23% of the users wore a helmet, despite the fact that it is compulsory according to the Greek regulations. Interestingly, the majority of the observed users didn't stop in the red light indication. These statistics indicate a highly aggressive traffic behavior of e-scooter users, who tend to the neglect the traffic rules.

Table 2. Descriptive statistics of categorical variables.

Variable	Categories	Frequencies
Gender	Male	240 (72.5%
	Female	91 (27.5%)
Distraction	No	289 (87.3%)
	Yes	42 (12.7%)
Helmet	No	255 (77%)
	Yes	76 (23%)
Existence of pedestrian waiting to cross	No	164 (49.5%)
	Yes	167 (50.5%)
Illegal crossing during red light phase	No	119 (36%)
	Yes	212 (64%)

Table 3 presents the statistics of the continuous variables of the analysis. The measured speeds before and after the change of traffic light indication are reasonable. The statistics of Table 3 show that e-scooters on average reduce their speed by 4.19 km/h within 3 s (assuming that the speed that was measured during the green light phase was maintained until the time that the traffic light indication changed from green to yellow). This speed reduction within the specific time period indicates a smooth deceleration in most cases.

Table 3. Descriptive statistics of categorical variables.

Variable	Mean value	Std. Deviation
Distance from traffic signal when traffic light indication changed (m)	15.16	7.58
Speed "before" (during green light phase) (km/h)	21.80	3.85
Speed "after" (3 s after the end of the green light phase) (km/h)	17.64	4.75
Speed difference (speed "after" minus speed "before") (km/h)	-4.19	4.31

As a next of the analysis, correlations between variables were investigated. More specifically, it was examined which variables affect the speed difference and the decision of the user to cross illegally or not. These two variables were considered as many indicators of the riding behavior in signalized junctions.

The speed difference was found to be correlated with the distance of the e-scooter user from the traffic light when traffic indication changed (Pearson's $r = 0.113$, p-value $= 0.040$). This correlation is presented in Fig. 3, where it can be seen that for distances up to 17 m, the speed difference scatters around −4 km/h. For distances greater than 17 m the speed reduction becomes lower. Interestingly, for distances up to 29 m that are cases where users accelerate instead of decelerating.

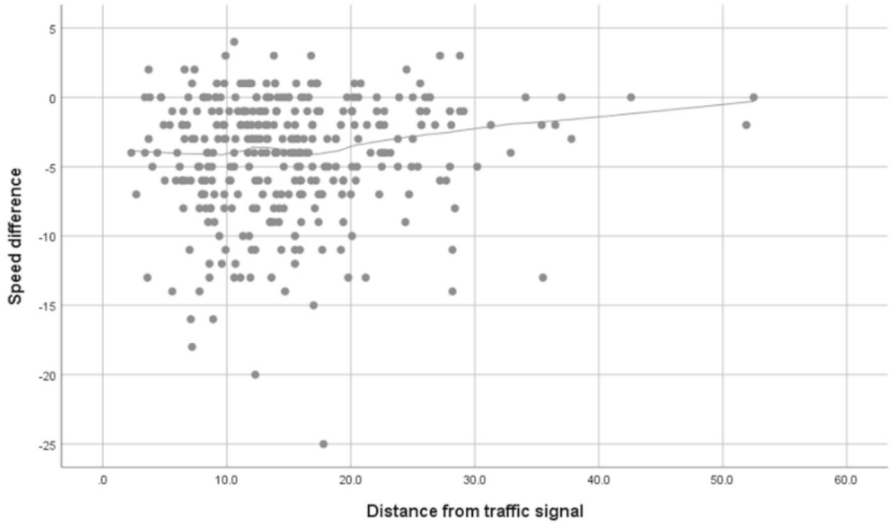

Fig. 3. Correlation between the distance of the user from the traffic light and the speed difference before and after the change of the traffic light indication.

The speed difference was also found to be correlated with the initial speed of the user, i.e. the speed he/she had during the green light phase (Pearson's $r = 0.321$, p-value < 0.001). Figure 4 presents the correlation between the two variables, where it can be seen that for moderate initial speeds (up to 20 km/h) the speed difference is close to the identified mean speed difference (4.19 km/h); however, the speed of e-scooters starts decreasing sharply for high initial speeds (higher than 22 km/h).

With regards to the decision of the e-scooter user to cross illegally the junction during the red light phase, several affecting factors were identified. One of these factors is the gender (p-value < 0.001). Figure 5 clearly shows that males are much more prone to crossing illegally the junction comparing with females. More specifically, the vast majority of males decided to cross the junction during the red light phase, while most females stopped appropriately.

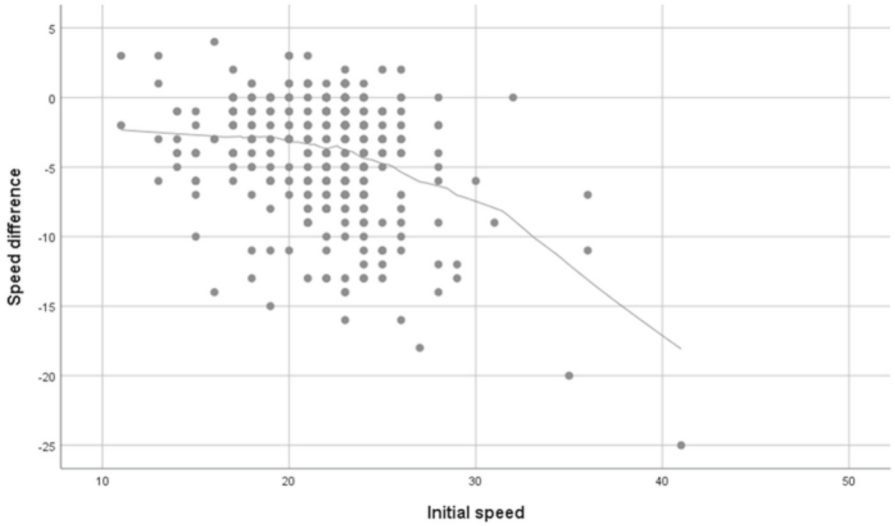

Fig. 4. Correlation between the initial speed and the speed difference before and after the change of the traffic light indication.

An additional factor that was found to affect the decision of e-scooter users to cross illegally or not is the existence of at least one pedestrian that was waiting in the pedestrian crossing of the junction (p-value < 0.001). From Fig. 6 it is identified that even in the case of having a pedestrian waiting to cross, most e-scooter users behaved illegally. However, the likelihood of behaving illegally is much higher in the case of having no pedestrian waiting to cross.

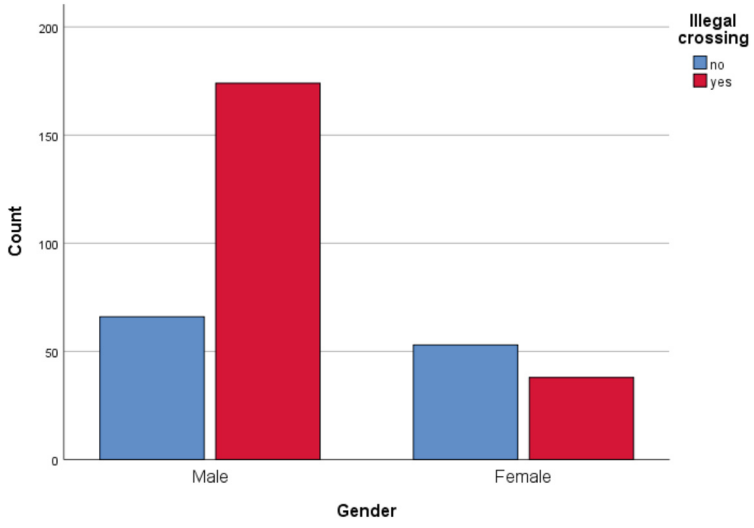

Fig. 5. Correlation between gender and illegal crossing during red light phase.

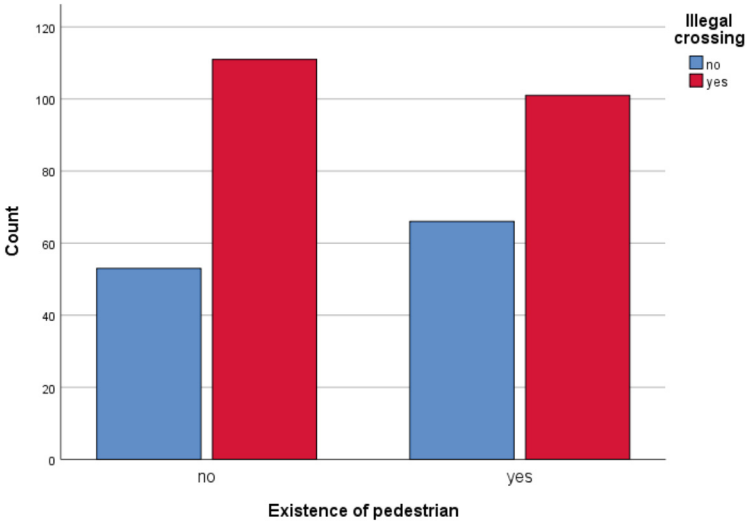

Fig. 6. Correlation between the existence of at least one pedestrian waiting to cross the road and illegal crossing during red light phase.

Illegal crossing during the red light phase found to be also affected by whether the e-scooter user was distracted when he/she was approaching the junction (p-value $<$ 0.001). Figure 7 shows that the majorities of both distracted and undistracted e-scooter users decide to cross illegally the junction; yet, the likelihood of performing this illegal behavior is higher among the distracted ones.

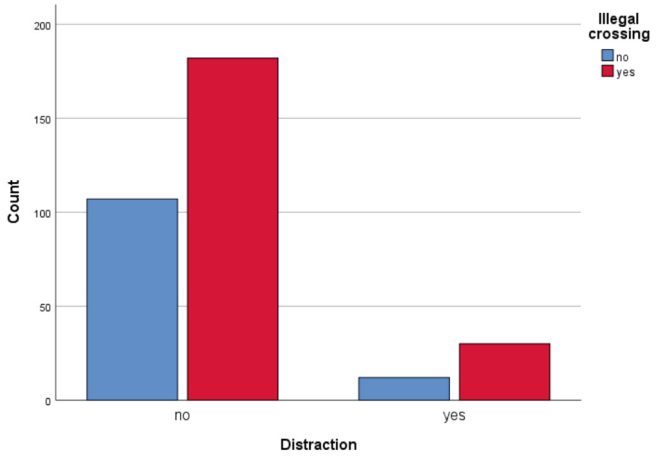

Fig. 7. Correlation between e-scooter user distraction and illegal crossing during red light phase.

Two additional variables were found to be statistically significantly correlated with the decision to of e-scooter users to cross illegally, the distance of the e-scooter user from the traffic light (p-value = 0.026) and the speed difference (in classes) before and after the change of the traffic light indication (p-value = 0.001). Figure 8 shows that those who crossed the junction during the red light phase were on average at a closer distance to the traffic light comparing with those that decided to stop appropriately. Figure 9 shows that those who accelerated or maintained more or less the same speed in the vast majority of

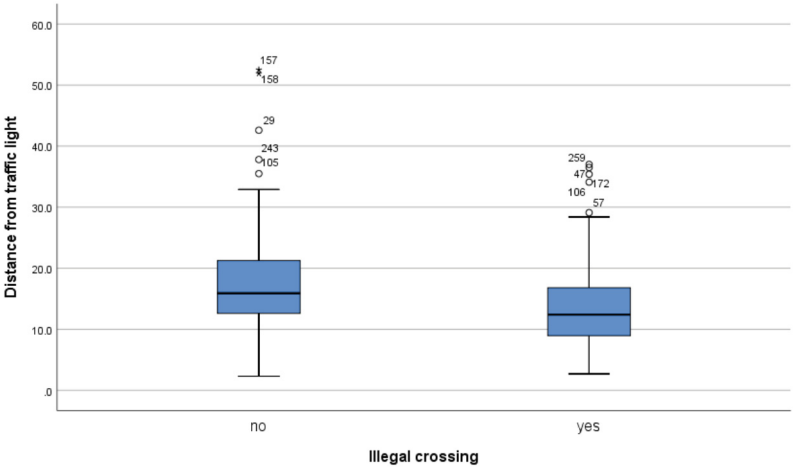

Fig. 8. Correlation between the distance of the user from the traffic light and illegal crossing during red light phase.

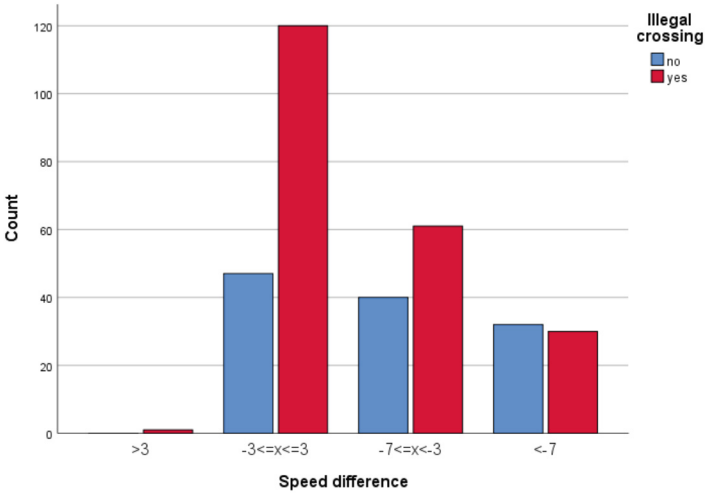

Fig. 9. Correlation between the speed difference before and after the change of the traffic light indication and illegal crossing during red light phase.

the cases decided to cross illegally, while those that decreased relatively abruptly their speed in most cases stopped appropriately.

4 Conclusions

The present paper aims to analyze the behaviour of e-scooter users at signalized junction, by utilizing observations on-site. During the observations, data about the geometric and functional attributes of the junctions were collected, as well as data about the characteristics and the behaviour of the e-scooter user. The collected data were initially analyzed descriptively and then correlations were investigated for identifying factors that affect the behaviour of the user. The speed difference before and after the change in the traffic light indication and the decision to cross during the red light phase or not were used as the two main indicators of e-scooter users behaviour.

The descriptive statistics show an overall high tendency for illegal behaviour among e-scooter users. According to the Greek regulations, e-scooter users are required to wear a safety helmet and not to use any device that could distract them. However, the percentages of e-scooter users that comply with these rules are low, especially for the safety helmet which was used by only 23% of the observed users. Even more alarming is the extremely high percentage (64%) of e-scooter users that ignore the red traffic light and cross illegally the junction.

The correlation analysis indicated that the aggressive behaviour of users is affected by several factors. Remarkable is the difference between males and females regarding the cases of illegal crossing during the red light phase. These findings complement findings from previous studies in the city of Thessaloniki, which show that males are more prone to undertake an illegal behaviour both as car drivers [19] and as pedestrians [20]. It becomes understood that independently of the road user category, males have a much more aggressive and delinquent traffic behaviour from females and this conclusion is in line with findings from other contexts/countries [21, 22]. Also, notable is the finding that most prone to violate the traffic light signal are those e-scooter users that are distracted. A previous study in the city of Thessaloniki focused on the crossing behaviour of pedestrians and identified that distracted pedestrians usually adopt a more cautious behaviour when crossing a road probably for balancing distraction's negative effects [23]. Thus, it seems that pedestrians and e-scooter users adapt their behaviour in different ways when they are distracted and there is a very high risk for e-scooter users who are involved in two illegal actions simultaneously (i.e. using a device that distracts them and crossing illegally during red light phase).

The abovementioned findings indicate that the situation regarding the introduction of micromobility vehicles in modern transportation systems is not yet mature. Still a lot of work needs to be done for educating users of micromobility vehicles. Also, these findings indicate that training activities are required, since it is not even certain that all users of such vehicles are aware of the existing regulations. Traditionally, road safety campaigns are focusing on driving and walking behaviour; however, cities are now accommodating new types of vehicles which are also very attractive to the youth and as such there is a great need for adapting the focus of the campaigns and considering these types of vehicles too.

The present paper is a first attempt to explore the riding behaviour of e-scooter users. Additional efforts are needed for delving deeper in this issue. Future research could be based on data that are gathered automatically and not with observers on-site. More specifically, data through cameras could be collected and analyzed using appropriate software for extracting e-scooter trajectories when approaching and crossing signalized junctions. Such accurate data could feed analyses for modelling e-scooter users riding behaviour at signalized junctions.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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Impact of COVID-19 on Urban Mobility: Empirical Evidence and Lesson Learnt

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Abstract. The impact of the COVID-19 pandemic on mobility was significant due to the lockdowns imposed by governments around the world. During these periods, a (oblivious) decrease in travel was registered (no travels for school, travels for work limited to some specific worker categories) with a modal choice that has penalized the public transport. But the question is: after lockdowns, have users resumed their travel habits or not? This paper tries to answer this question by considering two aspects: the modal choice and travel for shopping. A survey was carried out to investigate whether any changes were made in the user habits. The main findings are: i) for mode choice, the users struggle to go back to their old habits, with a generalized distrust of public transport and an increase in the use of the private car; and ii) for shopping, the users changed habits, for example reducing the quantity purchased but making more frequent purchases.

Keywords: COVID-19 · mode choice · travel behavior · public transport · city logistics

1 Introduction

The global impact of the COVID-19 pandemic prompted, in each country, the imposition of some restrictions that have attempted to reduce the spread of the virus. Such restrictions, ranging from social distance to general lockdown, combined with the fear of contagion, negatively affected the transportation field in terms of passenger and freight mobility. One of the legal acts issued by the authorities was the telecommuting (e.g. [1, 2]) imposing on some categories of workers the need to stay at home. In parallel, the closure of schools/universities contributed to the collapse of public transport. Obviously, this caused a sudden reduction in travel and a change in behavior related to those users who had to travel anyway [3]. In particular, the means of transport that required traveling together with other people were discarded, to switch to other modes ([4–7]): as an example, an increase in the use of bike sharing was registered in many countries ([8–10]). Another aspect to consider is traveling for shopping: also in this case, the impact of the pandemic disrupted user habits: for example, with an increase in the online shop (e.g., [11–13]).

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Return to normal is expected to be gradual, but it is not clear whether all users will resume their previous habits or not. Therefore, the aim of this paper is to try to give an answer to this question, considering both the mode choice and the travels for shopping. The survey, carried out in Italy in the first semester of 2023, has been designed to collect data related to a time period before the pandemic and after the national lockdown imposed in Italy. Data related to mode choice and purchase habits were collected.

The paper is structured as follows. Section 2 reports a review of the literature, both on mode choice and travel for shopping. In Sect. 3, the collected data are described, while in Sect. 4, the results are presented. Finally, the conclusions (Sect. 5) are drawn.

2 Literature Review

The pandemic caused modifications to the modal choice aimed mainly at reducing contact with other users. This means a sudden abandonment of collective transport (for those who used it) to move towards individual modes (e.g., car, bike, walking). Another effect was on the shopping habits, with a subsequent increase in e-commerce. The literature on this topic, although a short time has passed since the outbreak of the pandemic, is very extensive. Without the presumption of being exhaustive, in the next paragraphs a literature review related to mode choice and mobility for shopping related to the COVID-19 pandemic is reported.

2.1 Mode Choice

Public transport is perhaps the one that, among the different modes of transport, has suffered more from the impact of COVID-19. Almlöf et al. [14] analyzed the decrease in the use of public transport mode during the pandemic by correlating this choice with the socio-economic data of users. The finding is that the majority of users using public transport during the pandemic are those with low resources, which highlights a disparity in equity for users with different socio-economic characteristics. Abdullah et al. [15] examined travel behavior before and during the COVID19 pandemic, highlighting changes in user choices. From the data collected by the survey (extended to different countries), it emerged that during the pandemic trips are mainly undertaken for shopping and a significant abandonment of public transport in favor of private modes (e.g., car) was revealed. Parker et al. [16] studied how COVID-19 affected user behavior in the USA. From the data, it emerged that 75% of users used public transport less for two main reasons: the risk of COVID-19 transmission and the reduction in service frequencies. Shelat et al. [17], to understand user behavior at the beginning of the pandemic and assess behavior at different stages of the pandemic, designed a stated preferences experiment targeting train travelers in the Netherlands and calibrated a latent class choice model. Wielechowski et al. [18] studied changes in public transport mobility at different territorial levels (national and regional) in Poland, finding a (negative) correlation between public transport use and COVID-19 containment policies. A similar work, but at the urban level ([19]), revealed that 90% of users have stopped using or limited their use of public transport. Aydin et al. [20] evaluated changes in travel modes related to passengers in the city of Istanbul, the results demonstrated a consistent shift from public transport

to other modes, such as private car, bike and walk. Tiikkaja and Viri [21] found a 70% reduction in public transport in the city of Tampere (Finland) and discussed the actions implemented to adapt transport frequencies to the changing level of demand. Downey et al. [19] performed an analysis to understand what could happen to public transport at the end of the pandemic: the result is that more than 30% of users said that, after the pandemic, they will reduce public transport.

In terms of bike sharing, on the other hand, there has been an increase in demand, mainly from users who previously used collective transport [22]. Bustamante et al. [23] analyzed the factors that influence bike sharing in Barcelona before and after the COVID-19 lockdown. The results show that the main predictors in bike sharing choice are the trip distance and income level, other predictors are related to land use, weather, and infrastructural characteristics. Heydari et al. [24] estimated the effects of the COVID-19 pandemic on the London bike-sharing system by comparing the number of bike hires before and during the pandemic. The results demonstrated that, after an initial decline, the values returned to their previous levels. Hu et al. [25] examined the Chicago bike sharing system during the pandemic and estimated some models to foresee the average daily value of the hires. Among the predictors considered in the models, there are the attributes related to land use, the bike sharing station characteristics, and the income. Nikiforiadis et al. [26] studied the impact of COVID-19 on the choice of bike sharing; in this study (conducted in Thessaloniki, Greece), an increase in the use of bike sharing, (with users that shift from public transport and from private cars to bike sharing) has been pointed out. Teixeira et al. [27] examined the use of bike sharing during the pandemic in the city of Lisbon, observing that users used bike sharing to avoid public transport and maintain social distance during the trip. Kubal'ák et al. [28] analyzed how COVID-19 affected the use of bike sharing use in Slovakia, comparing such an use before and during the pandemic. An analysis of the trend of bike rent showed a fluctuating trend during the COVID-19 propagation. Similarly, Arias-Molinares et al. [29] analyzed the spatio-temporal patterns of use of shared services before and during the pandemic, revealing a decrease in their use. Azimi et al. [30] presented a case study related to the bike sharing during the pandemic, highlighting an increase (about the 30%) in ridership, during the COVID-19, with a related increase in trip duration. Basak et al. [31] evaluated the variation in bike sharing from the beginning of the pandemic to the first lockdown: an increase in bike rent was observed at the beginning of the pandemic and a consistent reduction during lockdown due to the lockdown because of the restriction measures adopted.

2.2 Shopping Mobility

The outbreak of COVID-19 drove users to increase their online shopping, in most cases even for goods that had previously been purchased in traditional stores.

Javadinasr et al. [32] explored the effects of the pandemic in the USA, also in terms of shopping mobility, there was an increase of 78% in grocery shopping comparing the pre-pandemic situation with the first wave and of 83% with respect to the second wave. Furthermore, users say that they are willing to buy online even after COVID-19. Koster et al. [33] evaluated the variation, due to the imposition of anti-COVID measures, in the number of users who move along the main shopping streets of the Netherland; they

found a 25 to 50% reduction in travels (depending on the measure considered). Villa and Monzón [34], analyzing online shopping trends of residents of the central area of Madrid, discovered the doubling of the online orders and evaluated the environmental impact of package transport vehicles. Ben Hassen et al. [35] investigated the impact of the pandemic on food shopping habits, finding that COVID-19 caused a decrease in shopping frequency and an increase in the quantity purchased. Music et al. [2] studied the variation in food online purchases, revealing an increase during the pandemic and the potential for further growth after the end of the pandemic. Focusing on grocery shopping, Xu and Saphores [36] investigated the habits of users in California during and after the pandemic: while there has been an increase in online grocery shopping, many users have continued to shop in 'traditional' stores. Bian et al. [37] examined the frequency of purchases at grocery stores during the COVID-19 pandemic, finding an increase of 20% immediately after the lockdown was declared. Recchia et al. [38] analyzed the use of channels for food purchases during the first lockdown in France, revealing variations in user habits by supply channel. Titiloye et al. [39] analyzed the supply channel (home delivery, curbside pickup, and in-store) chosen by users during the pandemic considering as relevant attributes the price, the shopping time, the delivery time and cost, and the travel time. Zhang et al. [40] investigated the demand for takeout shopping during the pandemic with the aim of identifying the factors influencing such demand. Some of these relevant factors are: population density, road density, house prices. German et al. [41] analyzed the propensity of users to choose a carrier during the pandemic, it emerged that variables such as user attitude, service quality, customer satisfaction affect user choice.

3 The Survey

The survey was designed in order to try to understand how the pandemic affected the preferences of the users in the COVID-19 period, specifically comparing the preferences in the pre-pandemic period and the preferences after the lockdowns suffered in 2020.

The questions were aimed at gathering information regarding both the modal choice and the variation (if any) of habits in travel for shopping (respect to the pre-COVID era). The survey contained a section dedicated to socio-economic data and some sections dedicated to the specific topic under investigation. The following paragraphs report some analyses of the surveyed sample.

The questionnaire has been developed with the aim of analyzing the travel behavior in the period before COVID-19 and in the period following the first Italian lockdown, both on systematic travels (e.g., home-work, home-study travels) and non-systematic travels (e.g., home-shopping). The sample consists of 217 respondents (of which 42% are women). Figure 1 reports some summary data: for the 68% of respondents, the age ranges from 18 to thirty years old, the 39% are employees, and the 49% have an annual income between 10,000 and 30,000 euros. Furthermore, the type and the number of vehicles owned by respondents is recognized (Fig. 2): as an example, the 49% own two cars, the 73% own a motorcycle or a motorbike, the 48% own two bikes, the 78% owns an e-bike.

Since the time interval between the pre-lockdown and the post-lockdown is quite large, the respondents were asked if their professional status had changed in the meantime

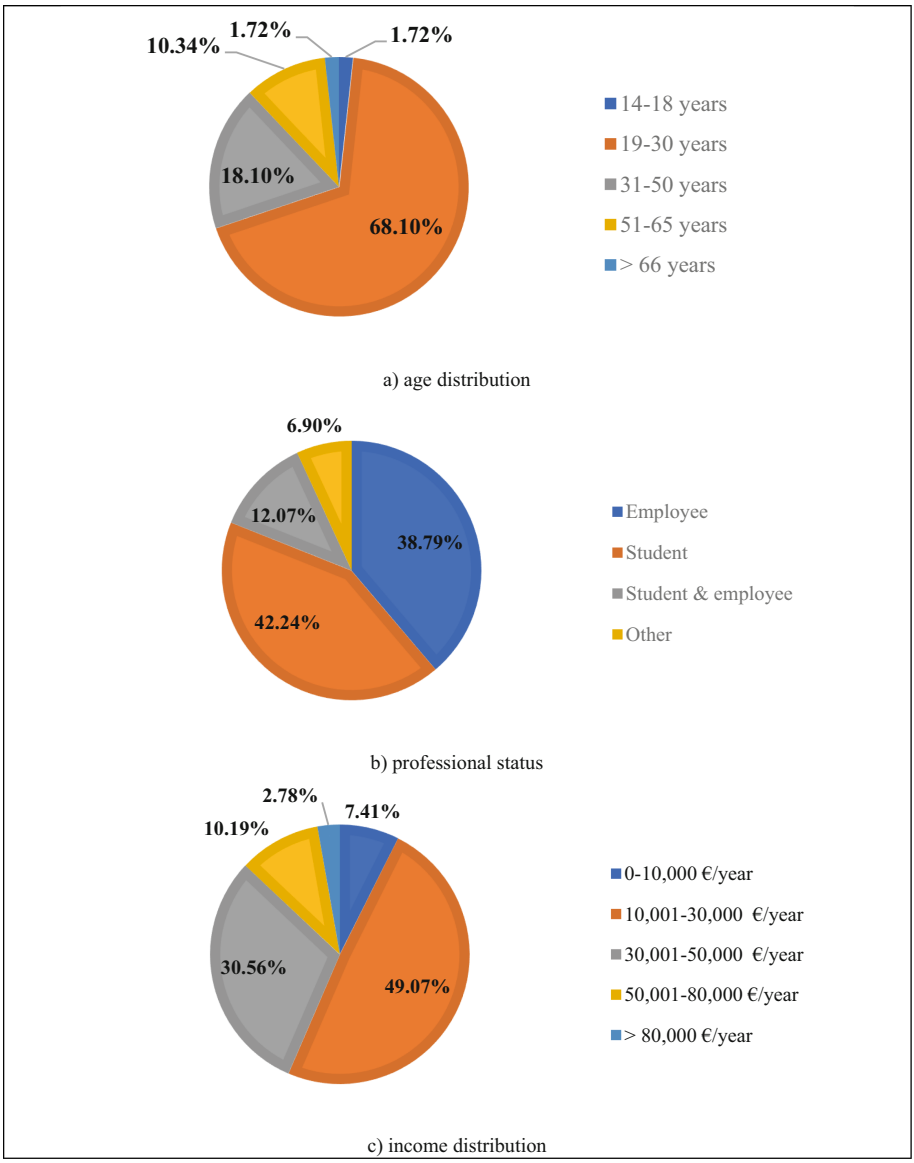

Fig. 1. The sample composition.

(e.g., from student to employee). This question can help to understate whether changes in mode choice are also linked with the transition from a professional status to another. It was revealed that (Fig. 3) about 66% of the respondents kept the previous status, about 20% changed the type of work, about the 6% passed from high school to university, about the 3.5% entered the world of work. It should be noted that around 5% enrolled in university.

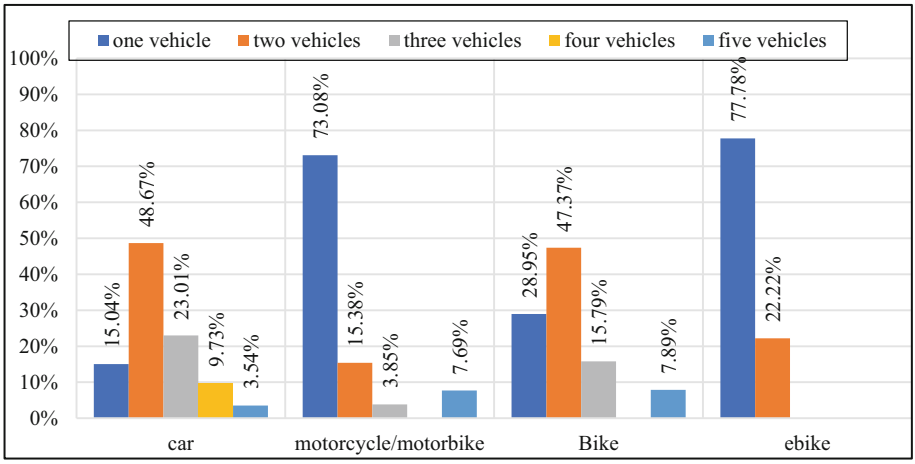

Fig. 2. Number and type of vehicles owned.

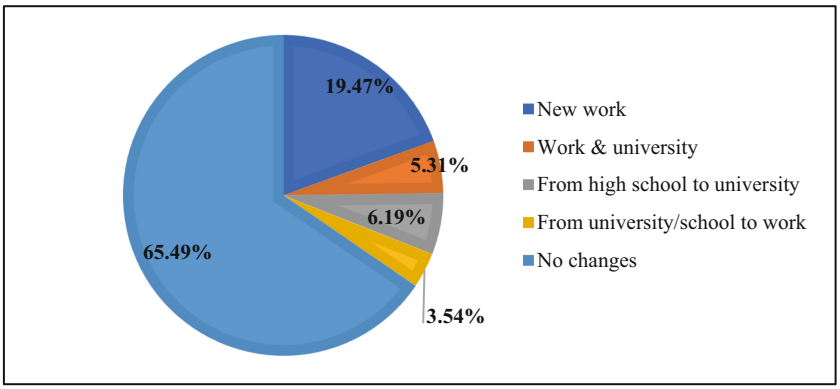

Fig. 3. Changes in professional status

Since shopping mobility is affected by the number of family members, a question on the composition of the household has been included. The responses showed that 68% of the families taking part in the survey are made up of at least 3 people, while 9% is made up of just one person.

4 Results

4.1 Data Analysis: Mode Choice

Analyzing the time distribution of the systematic travels (Figs. 4 and 5), no striking differences emerged between pre-lockdown and the post-lockdown. Outward travels are concentrated between 8 and 11 in the morning, the biggest differences are travels starting at eight o'clock (about 10%) and the afternoon trips between 3 p.m. and 7 p.m.. The

return travels are scattered in the afternoon with few relevant differences. As regards the non-systematic travels (Figs. 6 and 7), the situation before and after lockdown is very similar, with differences off less than 7%.

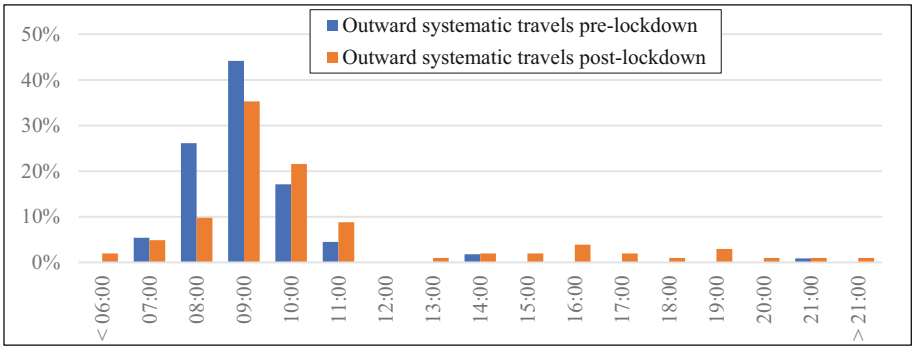

Fig. 4. Outward systematic travels.

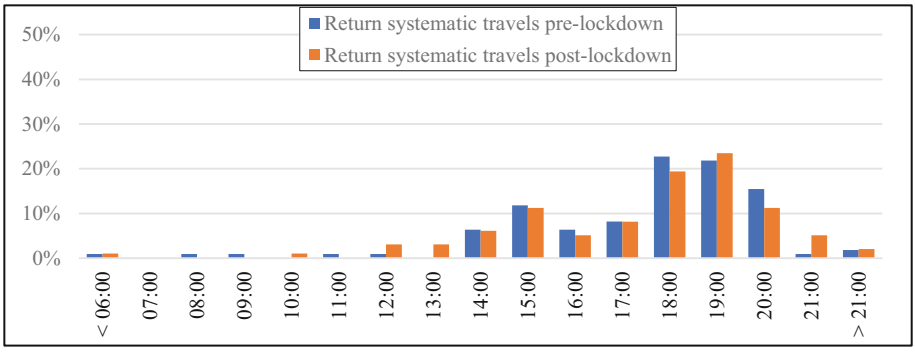

Fig. 5. Return systematic travels.

From the analysis of the mode choice (Figs. 8 and 9), it emerges that the public transport was already few used before the lockdown (38% for systematic and 16% respectively for non-systematic travels), its share goes down after the lockdown (18% and 6%, respectively). After the lockdown, the choice of public transport is reduced in favor of private transport and walking.

Focusing on the travels performed with the use of private transport (Figs. 10 and 11), among these also including walking, there are only small changes between the pre-lockdown and post-lockdown situation. In fact, for systematic travels, an increase of approximately 4% in the use of the car as a driver can be observed, accompanied by a decrease in the use of the car as a passenger. There is also a 5% decrease in travels by walking. The other percentages fluctuate by about 2%. Similar considerations can be done for non-systematic travels, where the use of two-wheeled vehicles (motorized or not) is also noted.

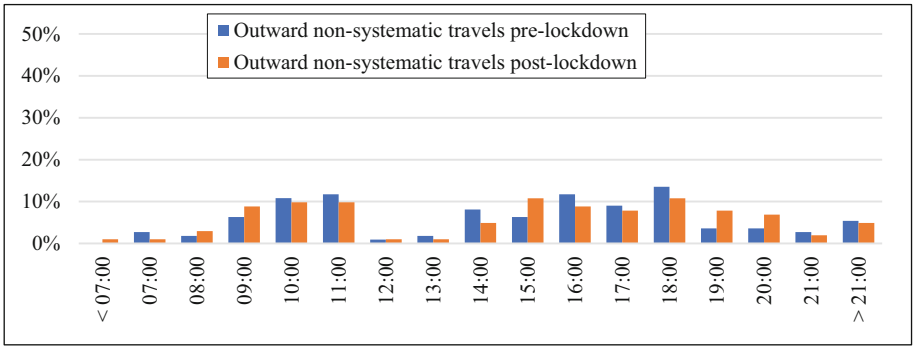

Fig. 6. Outward non-systematic travels.

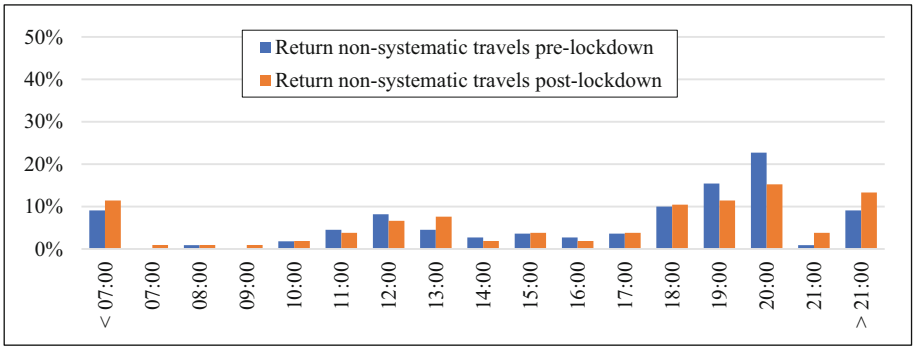

Fig. 7. Return non-systematic travels.

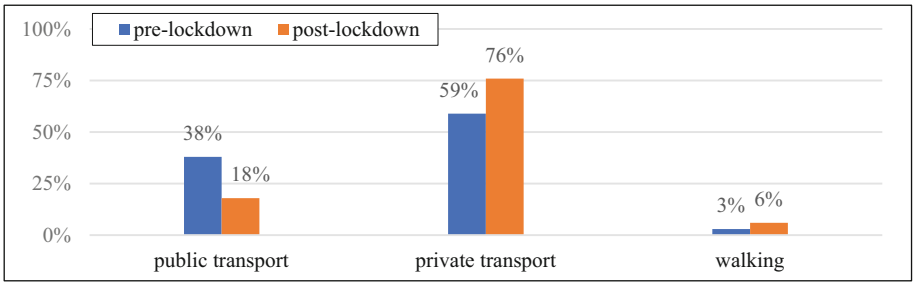

Fig. 8. Mode choice for systematic travels.

Focusing on systematic travels (Figs. 12 and 13), in relation to the choice of public transport, the weights given to the single factor remain substantially the same (the only obvious change is in the vehicles owned). The choice of private transport undergoes significant changes in factors consideration: in fact, while in the pre-lockdown situation

the main factors were the travel time and the comfort (44% and 51%), in the post-lockdown, factors such as social distancing and disinfection play a key role (18% and 14%, respectively).

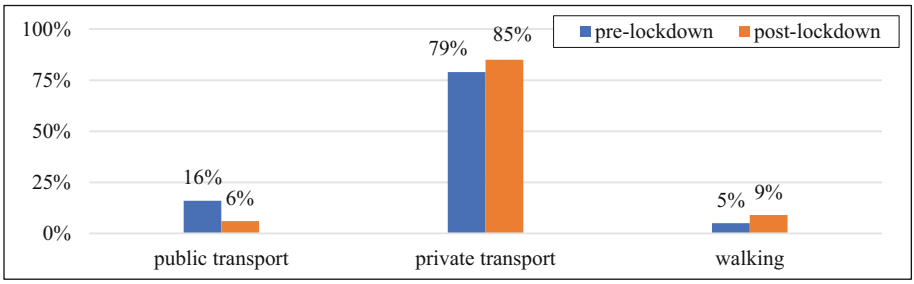

Fig. 9. Mode choice for non-systematic travels.

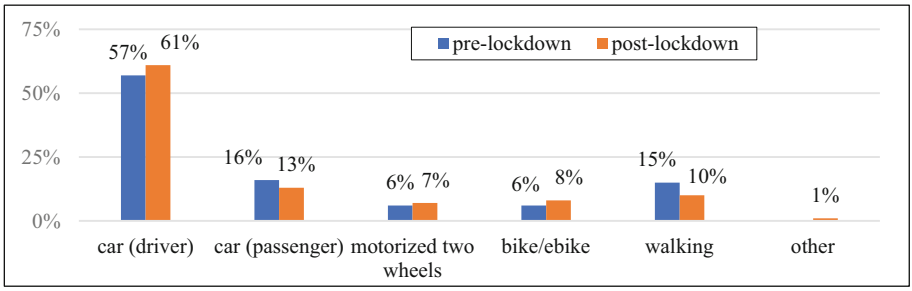

Fig. 10. Systematic travels with a private vehicle

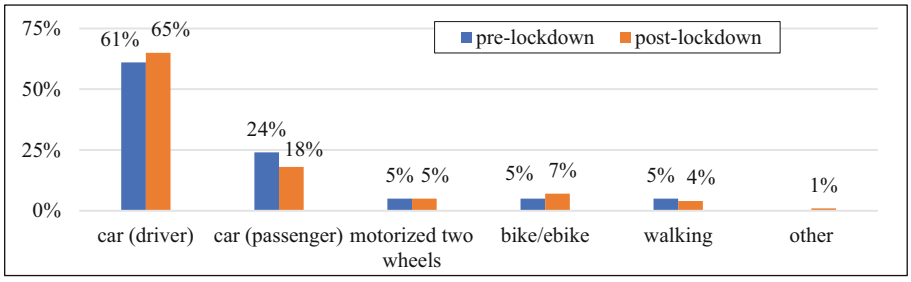

Fig. 11. Non-systematic travels with private vehicle

Focusing on non-systematic travels (Figs. 14 and 15), in relation to the choice of transport mode (public or private), the same considerations seen for the systematics can be made, the importance of the factors remains unchanged.

From the previous data, a multinomial logit model for mode choice was calibrated (by the Maximum Likelihood method) for the pre-lockdown and the post-lockdown scenarios. The modes considered are: car, bike (including also e-bike), public transport,

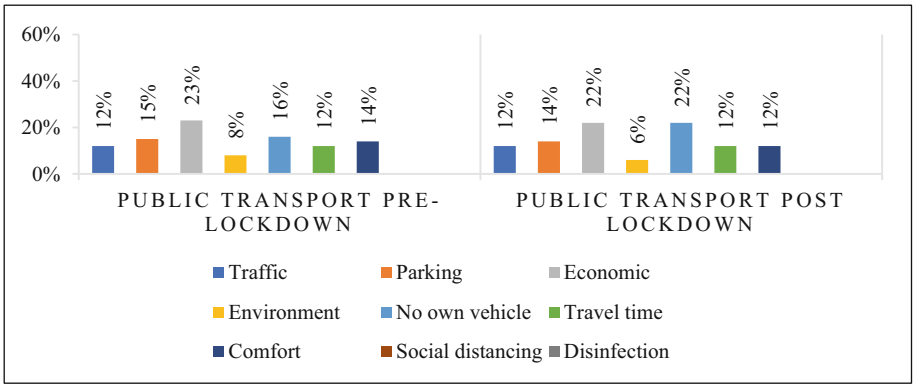

Fig. 12. Factors that affect the choice of public transport for systematic travels.

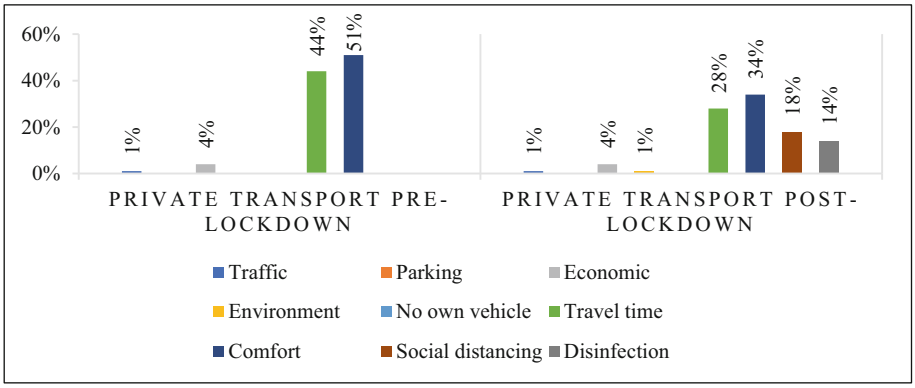

Fig. 13. Factors affecting private transport choice for systematic travels.

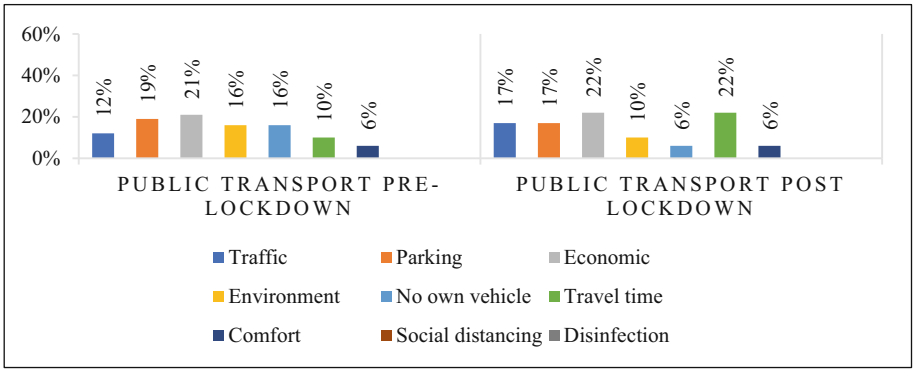

Fig. 14. Factors affecting public transport choice for non-systematic travels.

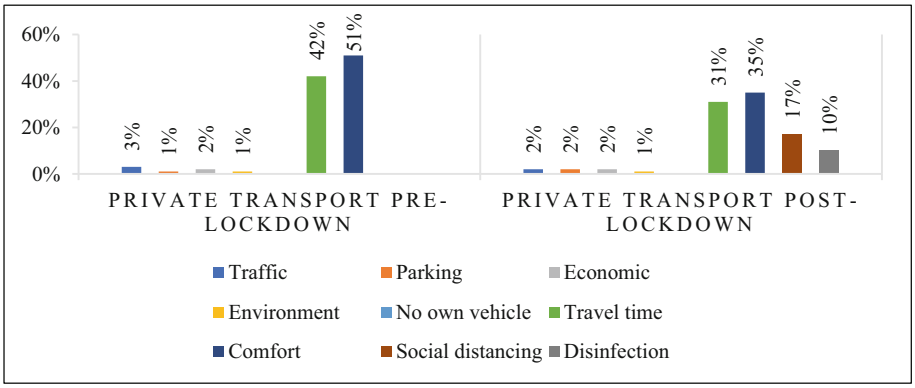

Fig. 15. Factors affecting private transport choice for non-systematic travels.

motorcycle, and by foot. The systematic utility for the generic mode m is specified as follows:

$$V_m = \beta_{dist} \cdot dist + \beta_{inc} \cdot inc + \beta_{ts} \cdot ts + \beta_{hh} \cdot hh + \beta_{fm} \cdot fm + \beta_{asc} ASA$$

where:

- *dist* is the distance of the travel;
- *inc* is the income of the respondent;
- *ts* is the time interval in which the travel begins, express in hours from the midnight;
- *hh* is the number of family members;
- *male* is a dummy variable equal to *1* if the respondent is male, *0* otherwise;
- *ASA* is the alternative specific attribute,
- β_x are the parameters to be calibrated.

This model allows us to simulate the mode choice of users under the two different scenarios, and to point out how the reciprocal weights are changed before and after the pandemic. Tables 1 and 2 show the calibrated parameters. The systemic utility of the alternative "by-foot" is the reference one and it is assumed to be equal to zero. From these values emerges that strong relevance of weight associate with the distance to travel by bus on long travel (for commuting trips). The user behaviors are quite changed before and after the pandemic. In fact, although distance represents a cost attribute, the reciprocal sign with respect to the base alternative, i.e. by-foot, needs to be discussed. When increasing the distance, users prefer to use a car more than ride a bike, as well as to use public transit services (public) for commuting trips. But the change of the parameter of bike shows that before the pandemic, users do not prefer the bike with respect to the foot, after the pandemic the attitude to use the bike is completely changed and they prefer to ride a bike than to go by foot. Similarly, increasing the family income, users prefer to use car more than other modes, however there is an inclination to go by foot (negative values of parameters after pandemic).

Table 1. Calibrated parameters for the pre-lockdown scenario

	β_{dist}	β_{inc}	β_{ts}	β_{hh}	β_{fm}	β_{asc}
car	0.354	0.103	−0.042	−0.030	0.098	0.785
bike	−0.283	0.642	−0.115	−0.284	0.786	−0.287
public	0.410	0.046	−0.066	0.108	−0.711	−1.227
motorcycle	0.212	0.046	−0.122	0.231	−0.164	−1.145
ρ^2	**0.48**					

Table 2. Calibrated parameters for the post-lockdown scenario

	β_{dist}	β_{inc}	β_{ts}	β_{hh}	β_{male}	β_{asc}
car	0.351	−0.260	0.258	0.823	0.911	−0.031
bike	0.089	−1.578	−0.424	0.700	3.639	0.284
public	0.707	−0.450	−0.481	0.748	0.042	−0.075
ρ^2	**0.43**					

4.2 Data Analysis: Shopping Mobility

The pandemic caused some changes in purchase habits: 36% of respondents have increased the amount of goods purchased on each trip, 10% have switched to online purchases, and 9% have changed the type of store. A 3% of the sample stated that they have increased the frequency of purchases (Fig. 16).

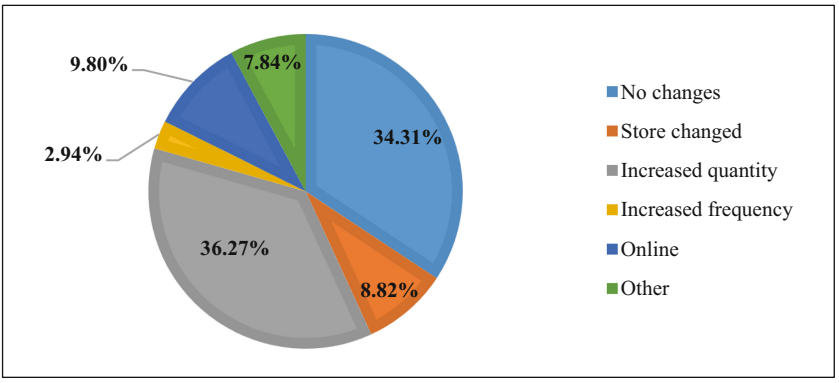

Fig. 16. Changes in users' habits

Another aspect that emerged in the survey is a change in the purchase frequency that, in general, decreases (excluding the fresh products) in the post-lockdown period (Fig. 17). In relation to expenses, a decrease of 7.93% which was seen considering

products as a whole, but when analyzing the single category of products, only the decrease in expenses for the purchase of foodstuffs (not fresh) should be observed (Table 3).

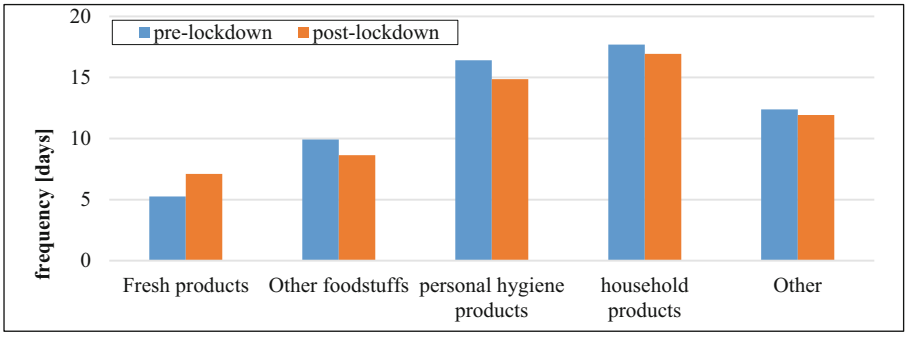

Fig. 17. Refresh frequency

Table 3. Comparing expenses pre and post the lockdown (reference: week)

	Pre-lockdown		Post-lockdown		Δ (on average)
Product	*Average [€]*	*Standard deviation [€]*	*Average [€]*	*Standard deviation [€]*	
Fresh	33.68	38.64	39.28	46.26	16.62%
Other foodstuffs	40.99	34.79	38.93	30.49	−5.02%
Personal hygiene	18.90	10.35	19.82	14.05	4.85%
Household	18.40	10.54	21.29	14.98	15.70%
Other	24.37	18.55	24.48	18.95	0.48%
All products	120.83	74.11	111.25	72.54	−7.93%

From the analysis of the days chosen for shopping (Fig. 18), it does not appear a very revolution between after and before the lockdown. Sunday continues to be the least used day for shopping; the other days are chosen (on average) in 15% of cases. On Saturdays there is a peak in the number of users who go shopping, less evident in the post-lockdown. Furthermore, in relation to the time interval and the transport mode chosen for shopping (Figs. 19 and 20), there do not appear to be any major changes. There are some small differences, but the trend remains the same.

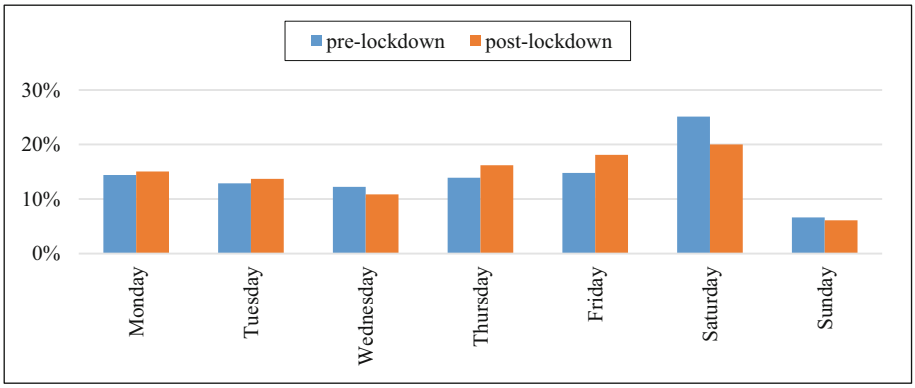

Fig. 18. Distribution of purchases by day.

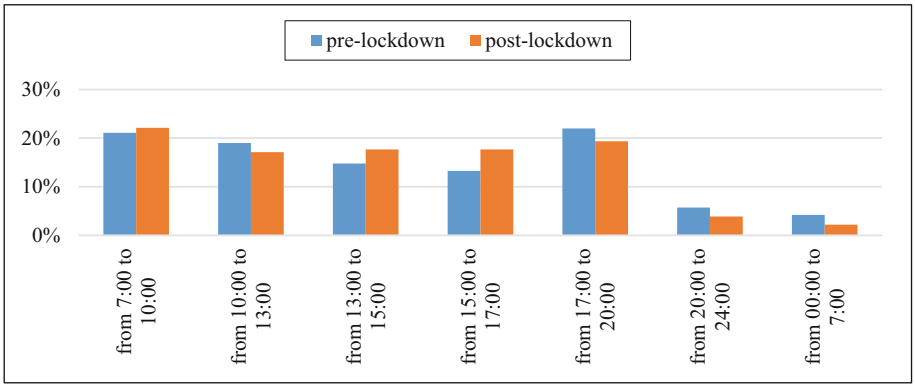

Fig. 19. Distribution of purchases by time slice.

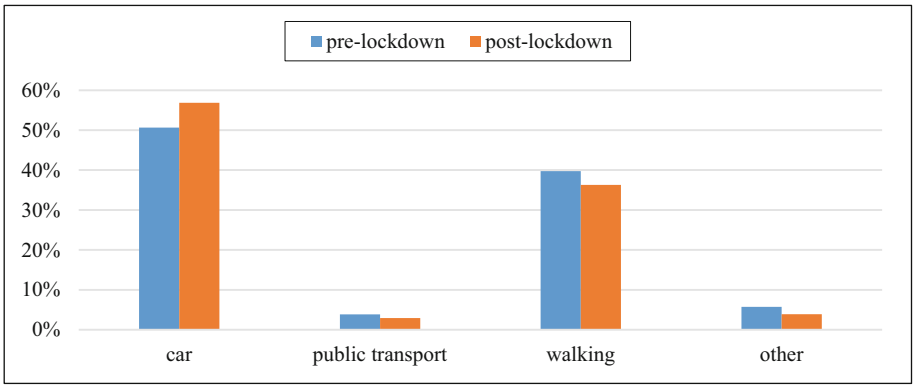

Fig. 20. Distribution of purchases by transport mode.

5 Conclusion

The rise of COVID-19 infection impacted all aspects of human life, and among these, the habits in travels. The data analyzed in this paper explored mode choice and shopping mobility, comparing habits before and after the lockdown in Italy. The respondents to the survey confirmed relevant changes in mode choice, in particular, the decline of modes in which it is made together with others. Thus, there was not only a collapse of public transport, but also, for example, of car sharing. Public transport has collapsed between 10 and 20%, depending on non-systematic or systematic trips. Similarly, the car as a passenger suffered a decrease of 3 and 8% .

From the analysis of the collected responses on mobility for shopping, there is no marked difference between behaviors before and after lockdown. There are slight changes in the distribution of purchases during the week, but the trend remains the same.

These results could be the starting point for defining policies to try to change users' choices in terms of transport mode for both systematic travels and travels for shopping, towards more sustainable means of transport ([42, 43]. This, for example, could reduce impacts due to the interaction between user journeys and those of commercial vehicles ([44, 45]). Future developments involve a further survey to understand whether habits acquired after lockdown have been maintained even in the decline phase of the COVID-19 disease.

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Urban Freight Transport and Emerging Information and Communication Technologies: Analysing End-Consumers Decision in Receiving E-purchases

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Abstract. This paper aimed to address the need for a comprehensive review of the attributes affecting end-consumers decision behaviour to fill the gaps by deepening the knowledge on socio-economic analysis. On the other hand, the evolution of emerging information and communication technologies are strongly impacting on end-consumers' decision behaviour and in particular the choice of receiving e-purchases. The goods reach the cities to satisfy end-consumers' needs. It is relevant for any city logistics scenario assessment to have a clear understanding of the attributes that guide the shopping behaviour process.

Keywords: Customer Decision Behaviour · Last Mile Delivery · Changes · City Logistics · e-ICT · E-purchase

1 Introduction

The necessity to investigate the shifting from in physical store to online has occurred over time because e-commerce is growing [1, 2]. Online purchasing increased approximately by 31.8% from the first quarter to second quarter in 2020. In addition, during specific periods (i.e., Black Friday) online shopping sales increased by 21.6%, while in store shopping sales decreased by 52.1% compared to 2019 [3]. End consumers around the world revealed a trend toward choosing online shopping from in store after 2020. For instance, there is a 15–30% growth in end consumers who purchase online for most categories of goods [4]. According to the European e-commerce report [5] the percentage of Internet users who bought goods or services online is increasing every year in European countries (37 countries: EU-27 and 10 neighbouring digital economies). Furthermore, Europe shows higher growth rates in business-to-consumer (B2C) e-commerce. This concept is becoming significant in urban freight transport. But in B2C, there is a challenge, such as a delivery failure [6–8] and more small and frequent parcels [9, 10]. These cause more freight movements in the cities and thus more negative impact, in economic, social, and environmental terms.

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Nowadays, end consumers have more options for last mile delivery alternatives than ever before. They would like to have personalised delivery. Their decisions affect the delivery operations and, subsequently, influence the sustainability of city [11–15]. The increase in online enquiries means that delivery services, particularly last mile delivery, have to be optimised, taking into account the improved network design for urban delivery points and also the need for contactless delivery [2]. In order to improve and optimise e-commerce and delivery related services, it is necessary to analyse and define the attributes that influence the end-consumer's decision behaviour in terms of last mile delivery. Through a careful literature review, this paper has identified a number of attributes influencing last mile delivery in e-commerce on a B2C concept. In general, the main existing and emerging alternatives for end consumers to receive their purchases are quite identified. However, it is a need to identify attributes that influence e-commerce trends and last mile delivery trends.

On the other hand, emerging information and communication technologies (e-ICT) are the cutting edge of the mess all over the world. It makes processes easier, optimises the operations, reduces the number of errors and has many positive aspects. The use of technologies has not yet reached widespread use in city logistics, and they can contribute significantly in improving e-delivery operations.

This paper evaluates recent studies on end-consumers decision behaviour and seeks to answer two main research questions:

1. What are the most commonly used attributes in the literature that affect end-consumers' decision behaviour and the choice in receiving e-purchases?
2. How do the attributes related to socio-economic analysis, e-ICTs affect the changes of end-consumers' decision behaviour and the choice to receive e-purchases?

For this purpose, looking at the current literature (see Sect. 2), the majority of the research focused on a single way of receiving e-purchases investigating the performances and assessing the choice of using it with respect the traditional one. Therefore, the need a further effort in such a topic germinates. Thus, an overview of the attributes affecting end-consumer purchase decision behaviour has been established. Subsequently, given that e-ICTs are providing new opportunities and are pushing toward new shopping patterns with significant changes in urban freight transport and logistics with substantial impact on the number of vehicles achieved and traffic impact produced, how shopping decision dimensions of end consumers can change is investigated. The results of the analysis will be adhered to identify the policies and measures that can be used to improve the level of sustainability in urban areas. The results can provide a reliable assessment for planners or decision makers to understand the key attributes contributing changing end-consumers purchase decision behaviour to identify the lever on which the influence is to reach the target volume of sustainability as defined by Agenda 2030. The results obtained from this overview can also be a guideline for operators, policy makers and researchers to improve the efficiency of the delivery service in relation to end-consumer's willingness to buy and the offered e-ICT opportunities.

The paper is organised as follows. The Sect. 2 introduces the literature review on papers with purchase decision in terms of last mile delivery on and investigates the state of the art. Although Sect. 3 recognises the last mile delivery alternatives in terms of end consumers and explores attributes for each one. Section 4 discusses survey analysis for

implementing the knowledge in a real case study. Conclusions and further development are presented in Sect. 5.

2 Literature Review

The literature review allows us to understand the most current and novelty topic, which can guide researcher discussions. It is for investigating modern and innovative approaches, observing the impact over many years, and discovering if gaps exist in the study of a given research field.

This section reviews papers on the way to receive e-purchases from the perspective of end consumers. The main papers are from 2018 to 2024, in English (see Table 1). The papers mainly focus on the analysis of end consumer preferences toward choosing the last mile delivery channel and the acceptance of new last mile delivery alternatives.

According to the data in Table 1, the literature review aimed at categorising the specific papers reviewed according to the following criteria:

- the papers that presented hypothetical implementation of last mile delivery alternative (designing, column *D*). In the list, they are represented designing pick up locker (*PL*), autonomous delivery robots (*ADR*) and crowdshipping service (*CW*);
- the papers that proposed ex- or post-ante assessment (column *A*);
- the papers that used modelling frameworks to compare different alternatives with the use of attributes with different levels (column *M*);
- the papers that represented implementation of survey or interviews in a real case study in a city or country (column *RC*) in order to investigate end-consumer preferences and choices;
- the papers that focused on main actors such as end consumer (column *ec*) or other (column *other*).

It is interesting to note that papers that represented modelling (*M*) are usually based on real case studies through surveys. The focus of the literature was on end consumers, but some papers also included other stakeholders such as retailers or municipalities.

Furthermore, PL, ADR and CW are the most popular instead of others in each category. Delivery to the trunk (TT) has a lot of issues in terms of safety and security, so there are fewer papers among other alternatives. It is important to note that click and collect service (CC) has been more interesting than the attended pick up point (PP) alternative. Thus, traditional mail (TR) occurs only compared with others. In more detail, insights and characteristics of existing and hypothetical alternatives are discussed in Sect. 3.

Then, the literature review shows us the need for research into some topics that have not yet been researched or are less researched. About 30% of the reviewed papers compared alternatives to investigate preferences. Furthermore, the main recognised source of information is a small number of papers that included all the alternatives. In addition, delivery to the trunk is an innovative alternative that has only recently appeared and is beginning to be piloted to become more popular.

Table 1. The literature review of papers analysed choice behaviour in receiving e-purchases.

#	Reference	Year	Alternative	Segmentation criteria						
				D	A		M	RC	Actors	
					ex-	post-			ec	other
1	Gatta et al. [16]	2018	CW[1]		x		x	x		
2	Punel et al. [17]	2018	CW		x	x	x	x		
3	Tiwapat et al.[18]	2018	TR[2], PP[3]		x				x	x
4	Vakulenko et al. [19]	2018	PL[4]		x			x	x	
5	Wang et al. [20]	2018	PL	x			x	x	x	
6	Buldeo Rai et al. [21]	2019	TT[5], PP, CC[6], PL			x	x	x	x	
7	Le and Ukkusuri [22]	2019	TT, CW		x			x		
8	Yuen et al. [23]	2019	PL			x	x	x	x	
9	Bjerkan et al. [24]	2020	TT, PP					x	x	
10	Chung et al. [25]	2020	ADR[7]		x					
11	Jaller et al. [26]	2020	ADR				x	x	x	
12	Kapser and Abdelrahman [27]	2020	CC			x	x	x	x	
13	Milioti et al. [28]	2020	ADR			x	x	x	x	
14	Pugliese et al. [29]	2020	ADR	x	x		x			
15	Simoni et al. [30]	2020	CW	x	x		x			
16	Taniguchi et al. [31]	2020	CW, PL		x					
17	van Duin et al. [32]	2020	PL	x		x	x	x		
18	Boysen et al. [33]	2021	PL				x	x	x	
19	Cai et al. [34]	2021	CW, TT, ADR, PL		x	x			x	x
20	Chen et al. [35]	2021	CC, PL, ADR			x	x	x	x	
21	Gatta et al. [36]	2021	ADR	x			x			
22	Maltese et al. [37]	2021	CC			x	x	x	x	

(*continued*)

Table 1. (*continued*)

#	Reference	Year	Alternative	Segmentation criteria						
				D	A		M	RC	Actors	
					ex-	post-			ec	other
23	Marcucci et al. [38]	2021	TT, CC			x	x	x	x	
24	Schaefer and Figliozzi [39]	2021	CC			x		x		
25	Tang et al. [40]	2021	PL			x		x	x	
26	Tsai and Tiwasing [41]	2021	PL		x		x	x	x	
27	Wieland [42]	2021	PL		x		x	x	x	
28	Edrisi and Ganjipour [43]	2022	CC		x		x	x	x	
29	Giglio and Maio [44]	2022	ADR				x	x	x	
30	Merkert et al. [45]	2022	CW			x	x	x	x	
31	Polydoropoulou et al. [46]	2022	TT, ADR			x	x	x	x	
32	Risberg [47]	2022	TR, CC		x				x	x
33	Cebeci et al. [48]	2023	CW			x	x	x	x	
34	Dong et al. [49]	2023	PL	x		x		x		
35	Garg et al. [50]	2023	ADR		x					
36	Koh et al. [51]	2023	ADR				x	x	x	
37	Mohri et al.[52]	2023	CW		x					
38	Ranjbari et al. [53]	2023	PL		x					
39	Wang et al. [54]	2023	TT, PL, PP, CC				x	x	x	
40	Alverhed et al. [55]	2024	ADR		x	x				
Results										
			CW	1	7	4	5	5		
			TR		2					
			PP		1	1	1	3		
			PL	3	6	7	9	12		

(*continued*)

Table 1. (*continued*)

#	Reference	Year	Alternative	Segmentation criteria						
				D	A		M	RC	Actors	
					ex-	post-			ec	other
			TT		1	4	3	6		
			CC		2	6	6	7		
			ADR	2	5	6	7	6		

CW[1] *– crowdshipping; TR*[2] *– traditional mail; PP*[3] *– attended pick up point; PL*[4] *– pick up locker; TT*[5] *– delivery to trunk; CC*[6] *– click & collect ADR;*[7] *– autonomous delivery robots*

3 The Alternatives for Receiving E-purchases

The following section introduces last mile delivery alternatives. The literature review allows us to identify attended and unattended alternatives as well as if the end consumers need to undertake a further activity (e.g., a further trip or stop along his/her usual commuter travel) by her/himself for obtaining the e-purchase (self-pick up *vs* not self-pick up). Besides, in the choice of the way of receiving the e-purchases, the end consumers can only decide the location putting the preferable addresses or/and the mode (e.g., crowdshipping and ADR). Such a possible classification is plotted in Fig. 1.

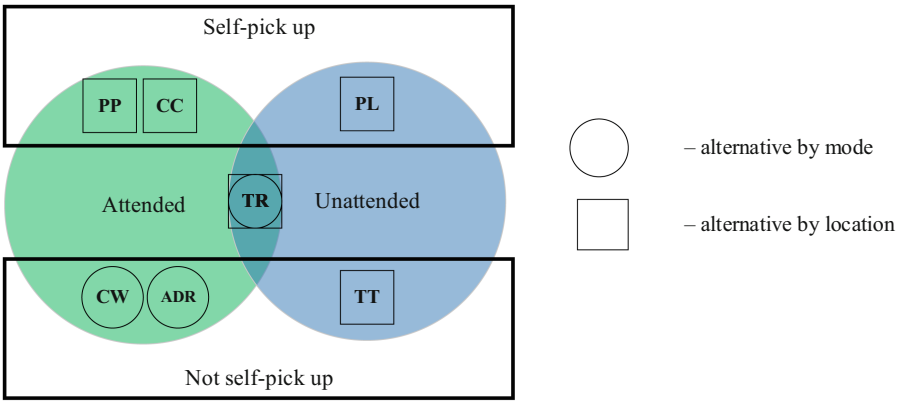

Fig. 1. Last mile delivery alternatives on the end consumer side.

3.1 Traditional Mail

It is a well-known concept that can be either attended or unattended. The alternative for delivering e-parcels to end consumers represents a company that provides last mile delivery services. The process is under the control from the sender's point to the end

consumer. The couriers and drivers are professionals and are responsible for the safety and security of the e-parcel. Usually, this alternative is more expensive and could provide auxiliary services such as delivery within a few hours, track and trace service, notifications, changeable address and time window.

Thus, traditional mail for end consumers is an alternative represents both in location and mode. The attributes were investigated including payment, lead time, time window and delivery price. Additional attributes are environmental impact, safety and security and reliability.

3.2 Delivery to the Trunk

The alternative delivery to the trunk has a location criterion. It is unattended by the end consumer. Access to the car trunk could be shared with the provider. Through a mobile application, it is possible to know the accurate location and time window for delivery. This is a novel alternative and nowadays carriers combine traditional mode and delivery to the trunk.

The attributes for delivery to the trunk are delivery time, time window and delivery price. Also, additional attributes such as safety and security make sense. When it comes to sharing access to one's own car, it is not just a matter of security for the e-parcel, but also for the belongings in the car.

3.3 Autonomous Delivery Robots (ADR)

The paper uses the term ADR for aerial delivery drones, sidewalk robots and droids (all existing autonomous delivery robots). The common characteristic for them now is attended delivery by end consumers. The ADR replaces the courier in last mile delivery service. They have a limited capacity, limited speed and restrictions. Today, it is a hypothetical alternative, although some real experiments are ongoing.

ADR has the following attributes: delivery time, time window and delivery price. Additional attributes are following environmental impact, safety and security, reliability and auxiliary services such as track and trace, notifications, changeable address and time window.

3.4 Crowdshipping

One of the ways to achieve a more sustainable city is a concept of collaboration. In addition, cities have a crowded flow of people with a concentration at Points of Interest (PoI). Crowdshipping is a service that includes drivers or non-professional couriers responding to the end consumer requests and can share the underused or unused capacity of their vehicles or themselves. Crowdshipping represents a mode for last mile delivery. It is an attended alternative by the end consumer. The website platform or mobile application that attracts freelance driver-partners. The attributes for crowdshipping are delivery time, time window and delivery price.

The challenge is the security of the information and the safety of the purchase. The respondent is someone who agreed to become a courier per the request. Thus, additional attributes are safety and security, also environmental impact and reliability. Auxiliary services such as track and trace, changeability and update notification are recognised.

3.5 Attended Pick Up Point

Self-pick up is an alternative represented by a location. The pick-up point is an attended alternative. It usually takes place in shops, cafes or at the post office. Pick up point has opening hours and is usually closed on weekends. It is a place that the end consumer can choose in a convenient area. The concept is a network that covers the city with high density. The attributes for this alternative are payment method, location, delivery time, time window and delivery price. Additional attributes include environmental impact, safety and security, reliability, and auxiliary services such as track and trace, notifications, changeable location and time window.

3.6 Click & Collect

The sub-alternative of the attended pick up point is a click & collect (i.e., "click & pick", "Research online, buy offline", "Buy online, pick up in store" or "Buy online, return offline" in the case of returns). The concept from the end consumer side is to buy online. Thus, this alternative was also emphasised because it involves restocking from the retailer's point of view. End consumers receive the e-purchase by self-picking up in the appropriate shop. The difference between an attended pick up point and "click & collect" is that the second has a shop network. It means like "booking" the item to ensure the availability and price of the e-purchase. The attributes are the same as for the attended pick up point.

3.7 Pick Up Locker

A well-known location alternative is a pick-up locker (i.e., automated parcel station). It is a storage medium used to facilitate the transfer of orders placed online for collection at a physical retail location. The locker can only be opened with the appropriate parcel locker key. The "boxes" form the networks of private companies. It is autonomous and available 24 h a day.

The unattended alternative has attributes such as location of delivery, delivery time, delivery price, and excluded time window. Pick up locker has additional attributes such as environmental impact, safety and security, reliability, and auxiliary services such as track and trace, notifications, changeable location and time window.

4 Survey Analysis

Section 3 has shown modern and innovative alternatives for last mile delivery. In addition, end consumers have leverage on delivery alternatives through their preferences. Thus, one important step is providing a socio-economic analysis of the study area to recognise the preferences according to end-consumer characteristics. Crocco et al. [56] findings show that socio-economic factors, consumer attitudes, and shopping mode characteristics influence the end-consumers' purchase decision behaviour.

The literature review allows us to investigate the main socio-economic characteristics that are helpful for visualising preferences in last mile delivery services. The research

by Comi and Nuzzolo [57] demonstrates that demographic and socio-economic changes can be a major factor in determining transport costs and related environmental impact.

The important characteristics of the respondent are age, income, family dimension and lifestyle, which influence preferences in last mile delivery. For example, young people are more familiarised with emerging technologies and are open to using them. In addition, they buy online more than others [58]. However students purchase less than other types of employees (about 1 purchase per week) [59]. In fact, empirical studies have indicated that males, the more highly educated, and people in the higher-income groups are more likely to buy online than females, the less well-educated, and lower-income groups [60, 61]. Srinivasan and Bhat [62] focused on overall shopping trip generation and report that females, people on high incomes, older people and households with children tend to engage in shopping more often than males, people on low incomes, younger people and households without children. According to employment status, Comi and Nuzzolo [58] showed that housewives undertake more trips than those in other types of employment, while young people travel less than older people.

Therefore, the survey allows us to analyse the socio-economic characteristics of end consumers. Then, it is possible to split them into different groups according to demographic affiliation, socio-economic status, some habits (such as purchase frequency) and familiarity with new technologies, etc.

Based on such literature findings, a survey was carried out in Italy in the first months of 2023. For the actual data collection, an online questionnaire was launched with 310 respondents. The survey consisted of a first part aiming to obtain socio-economic data and personal habits in shopping on line. Therefore, the stated preference part was proposed in order to reveal the possible choice behaviour in hypothetical scenarios.

4.1 Socio-Economic and Demographic Analysis

For the socio-economic analysis, answers were chosen such as: gender, age, current employment status, demographic affiliation, members of the family unit and level of education. In addition, preferences of transport mode were considered.

The respondents were almost equally divided by *gender*. Women make up 45% and men 55%. Most of the respondents said they were between 18 and 34 years of age (68%). Based on the existing survey experience, it is important to analyse the *current employment status* of end consumers. Thus, students represent 37% of respondents and full-time employees are 38%. End consumers in these categories are dependent on schedules and time windows. Predictably, the main attribute for full-time employees is a time window of delivery such as lunchtime or after working hours.

The *demographic affiliation* is as follows: 35% live in southern Italy, mainly in cities located in Calabria and Puglia, 50% live in central Italy, mainly in Rome and, finally, the remaining part (15%) live in regions of northern Italy. It will be used to analyse the existing last mile delivery system and the preferences of end consumers based on affiliation.

Looking more closely at *the members of the family unit*, it can be seen that 50% of answered families are made up of four members, while around 75% of people say that they belong to families in which at least two members are adults.

Regarding *the educational level* of the respondents, only 4% currently qualify higher than a master's degree, a qualification held by 38% of the respondents. Of the rest, 33% have a three-year degree (Bachelor's degree) and 26% have not yet completed high school.

Turning now to the travel habits of the respondents, it should be noted that around 80% of people have only a B driving licence, which allows them to drive all cars and certain types of motorbikes. When analysing end-consumers travel habits, 72% of respondents use their own car as a *preferred mode of transport*, followed by walking (preferred by 12% of respondents), public transport (7%) and motorcycle (5%).

4.2 Statistical-Descriptive Analysis: End-Consumers Decision Behaviour

In this section, 25 questions explore online purchasing behaviour for durable goods. It provides an overview on the data collected and allow to identify drivers of shopping behaviours. In particular, it examines the frequency of e-purchases, the delivery channel chosen and the preferred time window for the receipt of e-purchases. Answers to questions about the motivation for buying online and the most important attributes, when choosing the last mile delivery channel help to analyse end-consumers' preferences in more detail.

This section also analyses purchases made in the week before the survey. It provides real-time information on the behaviour and preferences of respondents' decisions about last mile delivery. The types of products purchased online, and the level of resilience was examined. These data help identify current trends and evaluate the effectiveness of last mile delivery strategies.

The result obtained was an assessment of the *frequency of e-purchasing* durable products. Durable goods include electronics, stationery, clothing and footwear, and household products such as crockery and vases. Products in the category 'durable goods with at least weekly replacement' are excluded, for example, tinned food. In terms of frequency of purchase, there is an almost even distribution of respondents who purchase on average several times a week (31%), once a week (23%) and less than once a week, but at least once a month (35%).

Each respondent is also asked to indicate the main *categories of products* they buy online. According to this, 84% of those questioned said that they mainly go online to buy clothes or shoes. This is followed by electronic goods, which are among the main items purchased online by 56% of the respondents, and the last category with a significant percentage of preference (44%) is household products.

Motivation to buy online rather than in a physical store. 44% of people buy online because it is more convenient. This is justified by the fact that it is apparently possible to buy online 24 h a day, unlike in a store. Other reasons include greater economic convenience (cited by 24% of the sample), a wider range of products (18%) and time savings (13%).

Last mile delivery *alternatives* such as home delivery (or workplace), pick up locker, pick up point and others were analysed. Respondents preferred home delivery (57%). The most used alternative to home delivery so far is delivery to a locker point (e.g., pick up locker at the railway station; 35%).

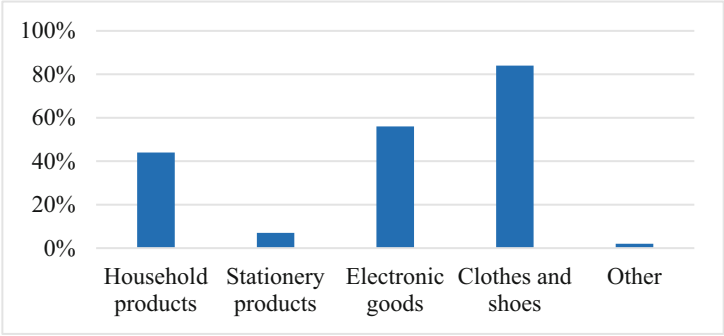

Fig. 2. Main categories of products to purchase.

The preferred *time window* is also one of the questions, too. The most convenient time window is between 14.00 and 16.00 when many workers have their lunch break and students return home (41%). Another time window is between 18.00 and 20.00, the time when the working day ends for most people, especially full-time employees.

Respondents were asked to identify the most *important attributes* that influence their purchase decision of the last mile delivery channel. Almost all respondents mentioned delivery time and price. Other attributes considered important by around 40% of respondents are delivery flexibility, i.e., the ability to choose a specific delivery day or time window or to receive the e-purchase at a pick-up point or locker. In addition, the security of the e-parcel is an important attribute for end consumers (traceability, confirmation signatures, or insurance).

The additional question aimed at understanding the maximum price a person is *willing to pay* to receive a parcel with standard dimensions, for example, 36 × 23 × 12 cm. 46% of the respondents are prepared to pay more than 5 euros, but no more than 10% of the price of the e-purchase. The other half say that they are not prepared to pay more than 5 euros, regardless of the price of the purchase.

Within the questionnaire, the sample is asked to select the main reasons for dissatisfaction arising from the choice of the last mile delivery channel. *Resilience* was analysed through this question. 84% of the sample cites late delivery as the main reason for dissatisfaction. The other main reason for dissatisfaction is difficulty in tracking (cited by 62%), while damage, loss of product and other reasons are only cited by a minority of the sample.

4.3 Previous Week's End-Consumers Decision Behaviour

As mentioned above, part of the questionnaire is dedicated to collecting information on the previous week's purchasing behaviour. Consequently, only 25% of respondents had not made any online purchases in the seven days before completing the questionnaire. On a more detailed level, 54% had made only one purchase and 21% had two or more.

As reported (Sect. 4.2), this is also reflected in the specific case of the last seven days, i.e. the *main type of product* purchased online in the last week is clothing and footwear, followed by electronic goods and household products.

Referring to the last order placed online, 42% of the sample said they had used an express *last mile delivery service*, such as Amazon Prime, which guarantees delivery within 2 days. 32% say they have used delivery to a pick-up locker, such as Amazon Locker. A residual share was recorded for other delivery channels. In addition, the preferred distance to receive e-purchases by self-pick up is closest to the home or workplace.

Particular attention is also paid to returns, as the majority of people (72%) declare the *returns policy* to be very influential on the choice of an online purchase. 85% of the sample report having made at least one return in their lifetime. If we look more closely at the last six months, we see that the percentage of people who have made a return in this period falls to 48%, a sign that the frequency of returns is not excessive. Around 70% of the respondents would prefer a home collection service rather than delivery to a specific physical location when making a return. The main barriers to returning e-purchases are waiting times for refunds or replacements (53%), the complexity of the returns process (26%) and the additional cost of returns (8%).

A cross-analysis between the age of the respondents and the preference for *last mile delivery channel* shows that as the age of the respondents decreases, the percentage of respondents in each age group who prefer to receive the e-purchases in a pick-up locker rather than at home increases. For example, 67% of respondents aged between 14 and 17 choose a pick-up locker as their last mile delivery alternative, whereas the percentage is very different for respondents aged 45 and over, with an average of 14%. Obviously, the opposite behaviour is found among respondents who prefer delivery to their home. This solution is most often chosen by over-65s (79%) and least often by the under-17s (33%). The graph below shows that there is a clear difference in choice between the under-34s, with an average of 44%, and the over-34s, with an average of 72%.

In terms of delivery *time window* preference, similar behaviours are found regardless of current employment status. What was said earlier (Sect. 4.1) for the sample in general applies specifically to students, employees, and retirees, with peaks of preference declared between 14.00 and 16.00 and between 18.00 and 20.00 (see below, Fig. 2).

The survey also showed how the motivation to buy online versus in-store is linked to current employment status. 62% of students say their main reason for shopping online is to save time and avoid travelling, while the majority of employees (77%) say that their main reason is to save time and money. Retired respondents who shop online say they do so mainly to save money and avoid travelling (73%) (Fig. 3).

Based on existing and hypothetical last mile delivery alternatives and done socio-economic analysis, the stated preference survey is most appropriate for investigating end-consumer preferences.

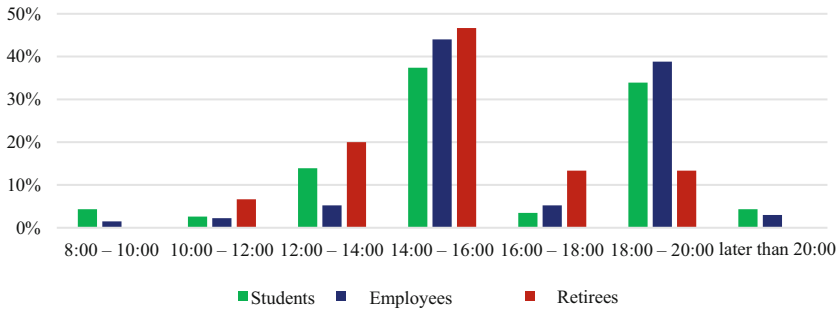

Fig. 3. Preferred delivery window in relation to current employment status.

5 Conclusions and Further Development

Nowadays, end consumers have more alternatives for receiving e-purchases than in the past. The paper provides a review of the literature on last mile delivery services and presents the results of a survey carried out in Italy. It provides valuable knowledge, useful for supporting both private and public sectors to reshape and optimise their last mile delivery services.

The growth of e-commerce and the business-to-consumer concept is having a strong impact on the changing behaviour of end consumers. It encourages service providers and researchers to identify emerging alternatives and key attributes of end-consumer preferences. Thus, the last mile delivery should be reshaped for optimising, including the existing and new services.

The literature review allowed us to emphasise existing alternatives such as traditional mail, attended pick up point and click and collect service, pick up locker, and modern alternatives such as delivery to the trunk, using autonomous delivery robots and crowd-shipping. In addition, the most commonly used attributes were investigated according to the literature affecting end-consumers' choice of receiving e-purchases. The main attributes are delivery time and price. Attributes such as payment method, lead time, time window and delivery price were investigated. Additional attributes are environmental impact, safety and security and reliability. Auxiliary services can also be track and trace service, notifications, changeable location and time window. The attributes were discussed in more detail in Sect. 3.

The attributes were investigated that related to socio-economic analysis and emerging information and communication technologies and affect the changes in end-consumers behaviour; and choice in receiving e-purchases. One of them is the preferred time window in terms of current employment status. The most convenient time window is between 14.00 and 16.00 when many employees have their lunch break and students return home (41% of the students' respondents preferred this time window). Another time window is between 18.00 and 20.00, the time when the working day ends for most people, especially full-time employees. The motivation to buy online is also linked to the current employment status. 62% of students say their main reason for shopping online is to save time and avoid travel, while the majority of employees (77%) say that their main reason is

to save time and money. Retired people who shop online say their main reason for doing so is to save money and avoid travelling (73%). A more detailed response is discussed in Sect. 4.

As mentioned above, end consumers are decision makers and their requests influence directly on existing and future last mile delivery alternatives. This is because the further step might be a stated preference survey, with the aim of investigating end-consumers preferences for last mile delivery alternatives. This paper has discussed the attributes, but the levels also need to be emphasised, which one the input for the design of the stated preference survey.

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Willingness to Subscribe to a Meal Kit Delivery Service: A First Investigation on Its Generated Impact in Italy

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Abstract. Meal Kit Delivery services are home delivery services of pre-portioned ingredients for meals' preparation. Meals are based on seasonal products sourced from local workers to shorten the supply chain. Rely on dedicated apps and home deliveries, meal kits aim to drastically reduce the time spent planning meals and purchasing food; moreover, since ingredients are pre-portioned in adequate quantities, the amount of food waste can be significantly minimized.

Main players in the meal kit delivery market are companies such as: HelloFresh; Blue Apron; Marley Spoon; Gousto, covering 50.91% of the revenues at worldwide level. The service is mainly widespread in the United States, but also several European countries started using it.

An online survey on the willingness to use meal kit delivery services is conducted to Italian inhabitants. The survey is organized in several sections: socio-economic characteristics of the respondents; habits about grocery (person in charge in the household and frequency; preference for large-scale retail trade or neighborhood shops; distance from shops and transport mode adopted; behavior in case of urgent need for specific products); personal attitudes regarding technology, online services, e-commerce, value of time, environment, food waste and food market sustainability; willingness to use a meal kit delivery service depending on type of subscription.

The main aim of the study, from the logistics and transportation side, is to evaluate potential reduction in trips for grocery and if changes on food logistic chains can be generated with consequent environmental benefits in terms of pollutant emissions.

Keywords: meal kit · food delivery · pollutant emissions

1 Introduction

1.1 The New Frontier of Food Delivery

Nowadays the desire to rediscover the house walls and the attention to the balance between home and work life are becoming stronger and stronger, along with a renewed centrality of well-being and healthy lifestyle. However, the frenzy of everyday life

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allows little time to dedicate to household and grocery, making difficult to obtain fresh ingredients and plan regular healthy meals.

The combination of all these factors makes solutions such as food delivery no longer enough: the need to know what you have on your plate and cooking it with your own hands is emerging forcefully.

For a few years now, a trend that intercepts all these needs has been gaining more and more traction: meal kit delivery (MKD), a home delivery service that offers boxes containing seasonal, quality, fresh ingredients, mainly sourced from local workers, semi-finished and pre-portioned (based on the number of people who consume the meal) for cooking a chosen recipe included itself in the box.

Worldwide, various companies offer this service: basically, through a dedicated app, you order online the dishes you like, whether for one, two or more people, and receive at home everything you need to cook them, including instructions. Usually, the proposed preparations are all attentive to a healthy and balanced diet and the leading companies in the sector offer a variety of dish options (e.g. Mediterranean, vegetarian, vegan, gluten free).

Born between 2007 and 2012 as a niche market, with first attempts in north Europe, Australia and United States, online MKD services have known a fast-growing. The global MKD services were valued at around 20.54 billion US dollars in 2022 and is forecast to exceed 25 million US dollars by 2027 with an expected compound annual growth rate (CAGR) of 15.3% from 2023 to 2030. North America gave the largest contribution to the market in 2022 (46.01%). However, Asia Pacific is the fastest-growing market (expected CAGR of 16.7% from 2023 to 2030) due to the increasing number of time-poor consumers in the region (i.e. China, Japan, and South Korea). In Europe, the northern range, especially Germany, has taken on an important role in the sector and the MKD service market is expected to grow at least in line with the global average [1].

Definitely, technologies and digitalization played a key role in its development: food shopping started to steadily move into the digital domain pushing towards online shopping options. The COVID-19 pandemic has been another major factor for its rapid evolution as people tried to avoid shopping in-store in the midst of the emergency causing a shift in consumer behavior still visible [2]. According to a survey conducted in 2020, 54% of US consumers cook more than before, and 22% order meal kits more frequently. Dining out has lost its appeal, especially among boomers and millennials that demonstrate increasing preference for staying at home and cooking or ordering in rather than spending money at restaurants [3].

1.2 Meal Kit Delivery: A Sustainable Option?

As mentioned, the growing awareness of the benefits of consuming fresh healthy meal options is a major factor in driving the shift in consumers attitudes, but the convenience of meal kits is not only given by receiving high quality products at home: this service can provide significant social benefits (e.g. time saving for meal planning and grocery shopping, that implies more time for leisure activities, family and/or work) and economic implications (e.g. encouragement for the development of small local business, so that many meal kit providers plan their menus a year in advance to contract with enough local suppliers before the growing season).

Moreover, meal kits have the potential to positively contribute to the environmental sustainability (e.g. shorter supply chains, fewer and shorter freight transport and so less traffic congestion, less food waste).

First, meal kit operators estimate that with meal kit boxes, 21% less food is wasted compared to those bought at the supermarket [4]. Food waste has a significant environmental impact (i.e. about 16–19% of the total Greenhouse Gas (GHG) emissions from the EU food system), not only for its disposal into landfill, but also for the huge waste of energy used through the entire supply chain (from production to consumers). Considering that, globally, approximately a third of the all food produced for human consumption is lost, and around 88 million tons of food is wasted only in Europe each year (i.e. according to data collected in 2023 by Eurostat, households cause more than half (54%) of the total food waste in the EU, with 70% of food waste arising at household, food service and retail [5]), the saving guaranteed by meal kits can have important consequences on the carbon footprint of the food supply chain as described by Scherhaufer et al. [6]. They illustrate the impacts of food waste in relation to the total food utilized, demonstrating that most of the impacts originate from the production step and food waste prevention can improve the situation as less food needs to be produced [6].

Also, Notarnicola et al. [7] identified food processing as a crucial phase in terms of environmental impacts (i.e. energy intensity and related emissions for the production of heat, steam and electricity), but they also found that logistics (i.e. transportation in terms of distances, number of voyages and transport modes) similarly contributes to carbon emissions.

Especially, the so called "last mile", the distance that the food travels through from the processor or retailer before entering consumer house, can notably affect GHG emissions reduction [8–10].

Last mile emissions account for 11% of the average grocery meal emissions compared to 4% for meal kit dinners. In fact, MKD services shorten the supply chain since the ingredients, to be fresh and not perished, usually arrive from local producers. Moreover, meal kit boxes are delivered all together on a single truck route (splitting the distance travelled over many customers, so that the actual miles per meal kit is much smaller). Consequently, the transportation pollutants related to meal kits are a little fraction compared to the total vehicle emissions that are normally detected when each consumer drives back and forth to the supermarket with a personal vehicle [11]. However, Allen et al. [12] point out that the benefits in terms of GHG emissions reduction are significant only if the route is specifically designed to optimize distances and waiting time, otherwise food delivery options become counterproductive. Analogously, appropriate truck/vehicle fuel sources can further reduce emissions (i.e. electric vehicles, bicycles). Thinking to transportation, positive consequences could be detected also in terms of traffic congestion due to less private vehicles driving in urban areas.

Another aspect to account for is the more packaging required by meal kits that could offset any energetic benefits of reducing food waste and miles travelled. Through a "lifecycle approach" that considers all the stages of each ingredient, from its creation to consumer home, the detailed research conducted by Heard et al. [11] found that the environmental impact of that packaging is counterbalanced by meal kits savings in emissions due to less food waste and fewer miles of transportations compared to grocery

stores (i.e. 8.1 kg of carbon dioxide equivalent for a "grocery store-bought meal" *vs* 6.1 kg cooking that same meal using a meal kit, around 33% less GHG emissions).

Pre-portioned ingredients and a streamlined supply chain seem the key factors for minimizing the carbon footprint of meal kits. Additionally, using eco-friendly packaging (e.g. selecting recycled and recyclable materials, as well as minimizing the amount of packaging), and favoring seasonal local organic products (for minimizing production processes and transport related emissions) can further make meal kits a sustainable option [10].

According to Yoon et al. [13], meal kits with organic, local, and pre-cut ingredients prepared in fully recyclable packaging induce consumers to opt more willingly for MKD services. Same attention of consumers to quality of product, minimization of wastage (in all aspects, whether as time and effort or as food waste), quality, functionality, and visual appeal of meal kit packaging was found by Sharnock who investigated what factors consumers mainly consider for deciding to subscribe to a MKD service [14].

Despite all this, still a minority of consumers regularly ordered fresh food meal kits to cook at home. A major drawback is their high cost. According to a survey conducted in 2020 [2], around 13% of high-earners in US planned to spend more for MKD services as a consequence of the COVID-19 pandemic. Nevertheless, people with a yearly income lower than 100,000 US dollars were much less prone towards this tendency, pointing out that MKD services still have obstacles to solve in order to gain mainstream popularity.

Anyway, they can be more cost-effective than ordering in or eating out. In addition, they can make accessible high-quality ingredients otherwise not affordable, and allow to save money by buying only the amount of food needed.

1.3 Objectives of the Study

Since transport logistics, as previously discussed, is one of the most important phases for the overall food supply chain in terms of environmental impacts, creating advances in transportation logistics to reduce last mile emissions plays a key role. To succeed in this goal, the understanding of customers attitudes, tastes, habits, inclinations and perceived value is fundamental. Bearing this in mind, this study aims at analyzing the potential of MKD for making significant changes in the overall food supply chain mainly by reducing private vehicle transport to and from grocery shops.

Considering that MKD services are a relatively new topic and limited specific literature exists on this matter, exploring the potential user segment and its characteristics is a primary need. The proposed investigation, carried out through an online survey on the willingness to use MKD services in Italian metropolitan urban areas, can provide useful insights for better understanding consumers perceived costs/benefits and identifying the main factors that could induce consumers to subscribe to a MKD service and how their behavior could change, mainly in terms of transportation. Consequent implications for both researchers and operators can be detected providing the basis for further research on the topic.

What just described has been developed in the paper as follows: Sect. 2 illustrates the methodology adopted for the survey and the related results analyzed with a view to identifying the most relevant factors for subscribing to a MKD service. Based on survey results, Sect. 3 proposes a computational procedure for estimating the potential of MKD

services to reduce travelled distances and related externalities (i.e., pollutant emissions). Section 4 deals with the implementation of a behavioral model able to generalize survey outputs and provide useful information for forecasting potential MKD services users. A final summary section concludes the contribution.

2 Methodology

Given the fact that people often act differently from what they state, in order to capture the most realistic picture of consumers' behavior and a solid understanding of their intentions, the paper combines revealed preferences (RP) and stated preferences (SP) surveys to investigate current knowledge about MKD service and the willingness to use it as a function of different types of subscriptions and attitudes of respondents. Specifically, SP come from direct questioning and create scenarios using hypothetical data, whereas the approach based on RP relies on data coming from the observation of actual behaviors (it assumes that users' preferences are revealed by their actions and habits).

The survey (in Italian language), directed to consumers, was conducted online through the LinkedIn social media network.

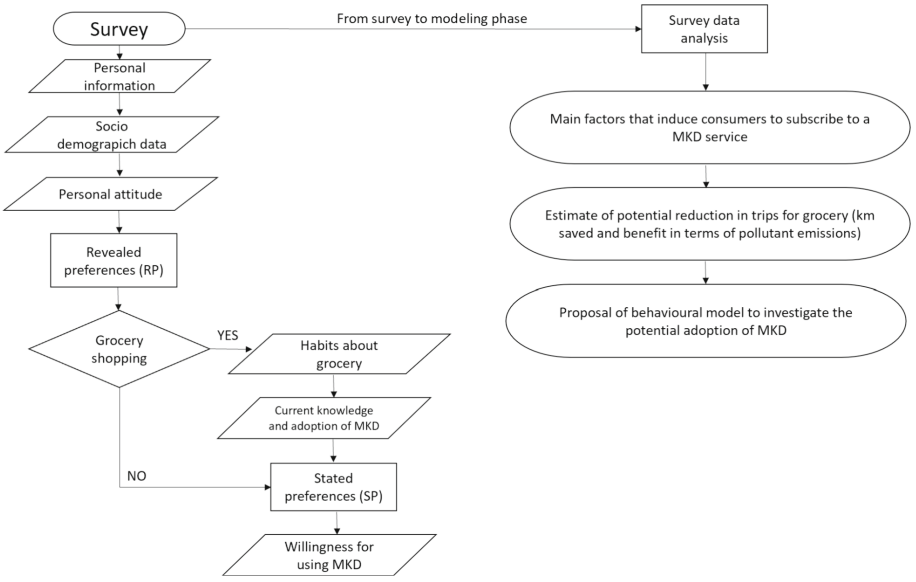

Fig. 1. The proposed methodology: from survey structure to the modeling phase.

Figure 1 schematizes the methodology adopted in the study: the survey has been organized according to different sections, including the RP and the SP ones. Data collected through the survey feed the modelling phase, which terminates with the proposal for the behavioural model for MKD demand forecasting.

2.1 RP and SP Survey

Survey Design. The survey, conducted between January and February 2024, involved 150 respondents. The questionnaire was preceded by an introduction aimed at emphasizing the novelty of MKD service and focusing attention on some main keywords such as "food industry", "food trends and future", "sustainability". Despite the potential impact on the response rate as well as on the overall representativeness of the sample, incentives were not offered to respondents due to budget constraints.

The survey consisted of 5 sections as follows:

(i) personal data section (age, gender and employment status);
(ii) socio-demographic data section (further data on users and their household, such as number of household members, number of household members with an age lower than 15 years old, household vehicle fleet);
(iii) habits about grocery (person in charge in the household, frequency; preference for large-scale retail trade or neighbourhood shops; distance from shops and transport mode adopted; behaviour in case of urgent need for specific products);
(iv) personal attitudes regarding technology, on-line services, e-commerce, value of time, environment, food waste and food market sustainability;
(v) willingness to use a MKD service depending on type of subscription.

All the factors considered in the survey were based on a comprehensive literature review related to MKD, as well as on previous research experience and knowledge in the field of e-commerce and e-grocery.

Survey Results. Table 1 shows the socio-demographic characteristics of the users' pool (data gathered through sections (i) and (ii) described in the previous section). First, it should be noted that the gender of respondents is quite uniformly distributed, as well as their age (except for the age higher than 67, probably due to very low attitudes toward technology that, consequently, makes this population segment little interested in using services such as MKD). Most of the sample (76%) is employed, aspect that makes the analysis more relevant since the adoption of MKD is mainly reported for people that have no time available to prepare meals. Further, the number of household members was recorded, together with the number of household members younger than 15 years old: the latter information was specifically investigated since often teenagers and children do not appreciate meals generally proposed by MKD services [14].

Household vehicle fleet was also collected during the survey as direct indicator of income levels: as a function of number of household members and number and type of vehicle fleet, four income levels have been derived (low: 38%, medium: 27%, high: 24%, very high: 5%). 6% of the sample did not contribute to derive the income level since the respondent declares to not have any vehicle.

Section (iii) investigated the habits about grocery: 77% of the sample usually goes grocery (alone or in collaboration with another household member). Hence, this portion of the sample was asked other questions relating to grocery shopping, whereas the remaining 23% was redirected to a subsequent section of the survey. Mostly, shop is conducted using a car (69%) or by foot (29%); generally, supermarket and large-scale retail trade centres are visited (58%), small retail stores or food markets only for 10% of the respondents, 33% usually visits both. The choice is strictly correlated with the

Table 1. Socio-demographic description of the sample interviewed

Sample characteristics	
Age	[%]
18–29	28.0%
30–39	18.0%
40–49	22.0%
50–67	27.0%
>67	5.0%
Total	100%
Gender	
Male	41.0%
Female	54.0%
Not specified	5%
Total	100.0%
Employment Condition	
Employed	76.0%
Student	11.0%
Retired	7.0%
Unemployed	5.0%
Total	100.0%
Number of household members	
1	12.0%
2	28.0%
3	32.0%
4	22.0%
>4	6.0%
Total	100.0%
Number of household members (<15 years old)	
None	73.0%
1	18.0%
2	5.0%
>2	3.0%
Total	100.0%

distance one is willing to travel to reach the store location: in case of large-scale retail trade, travelled distances are mainly between 1 and 3 km (42%), but also higher distances are considered (17% between 3 and 5 km). In case of small retail stores or food markets, 88% of the sample stated distances lower than 1 km. The travel mode and the type of shops visited for grocery are interconnected: 72% of users using a car prefers to shop in supermarkets and large-scale retail trade centres; instead, if moving by foot, the type of shops visited are more distributed (25% supermarkets and large-scale retail trade centres, 28% small retail stores or food markets, 47% both type). In the event of urgent need for missing products, the choice for the grocery shop type changes: most of the respondents searches for the nearest shop located within a maximum walking distance of 1 km (94%), regardless of store size and products variety. Finally, a high share of respondents carries out shopping on the way back from work, important finding strictly correlated to the need of optimizing time and activities (thus, trips) during workdays.

About the frequency related to grocery shopping, 40% of the sample makes it once a week, 34% twice a week, 19% more than twice a week ("frequent shopper") and only 7% not every week. On average the frequency for grocery shopping is equal to 1.77 times a week.

Moving to section (iv) related to personal attitudes:

- 64% of the sample has a medium to high attitude toward e-commerce (with regard to both products and services), 54% is familiar with social network, 65% is interested in new technological solutions;
- more than 80% of the sample found economic convenience and time saving fundamental factors for joining an online service; instead, environmental concerns have lower importance with respect to previous factors;
- most of the sample finds buying healthy and tasty foods, as well as avoiding food waste, main factors influencing grocery shopping; eating variedly and food price are considered important, but not as the previous ones; finally, preparation time and recipe complexity are of intermediate importance.

In the last part of section (iv), the inclination in improving habits related to grocery shopping and meals preparation are investigated. Quite surprisingly, the time spent for shopping and the time spent for planning meals were not found to be critical factors. Instead, the respondents declared the desire to contribute to food waste reduction. Regarding increasing the variety of meals and learning new food recipes, the sample is divided between those who do not consider them important and those who consider them noteworthy but not crucial aspects for choosing.

Finally, the willingness to use a MKD service depending on different types of subscription was investigated in section (v). The fact that MKD is not yet widespread in Italy is easily recognizable in sample answers: 50% of the respondents has never heard of it, 29% has heard of it but is not sure on how the service work, only 22% has a clear knowledge of what MKD can offer.

The analysis of subscription's scenarios proposed shows that 23% of the sample would join the service with the current conditions (i.e. accepting the cost proposed by the major MKD platforms existing today: approximately 6.80 €/MK with a minimum order of 6 MK/week); 38% of the sample would join the service in the event of a decrease

of meal cost (depending on the scenarios:11% if the cost is 5.90 €/MK with a minimum order of 6 MK/week, 12% if the cost is 5.00 €/MK with a minimum order of 6 MK/week, 7% if the cost is 3.00 €/MK with a minimum order of 6 MK/week, 8% if the cost is 3.00 €/MK without minimum order), whereas the remaining 39% would not join the service even in the event of a drastic reduction of the cost.

Correlation Between User's Features, Attitudes and MKD Subscription. A first analysis is conducted computing the percentages of respondents that would potentially subscribe to the service as a function of different values of their features and attitudes.

The aim is to find some useful dependences (we refer to as "correlation", despite classical correlation measures are not computed) that could be adopted in the following of the study and specifically in the behavioural modeling phase. The survey underlines a high correlation between age of respondents and their potential MKD subscription: that is, younger respondents showed a higher willingness to subscribe the service (Table 2). Moreover, some attitudes have a certain impact: it is the case of the familiarity with social network, the importance of time saving in on-line shopping and avoiding food waste (Table 3). More the respondent recognizes the importance of these factors and more is the percentage of potential MKD subscription.

Table 2. Correlation between age and MKD subscription

MKD potential subscription		
Age	Yes	No
18–29	88%	13%
30–39	70%	30%
40–49	56%	44%
50–67	38%	63%
>67	29%	71%

Table 3. Correlation between attitudes and MKD subscription

MKD potential subscription percentage [%]			
	Attitude toward adoption of social media	Importance of time saving for on-line services	Importance of avoiding food waste in grocery shopping
Very Low	40%	52%	33%
Low	50%	54%	50%
Average	64%	61%	47%
High	75%	62%	68%
Very high	83%	86%	78%

3 Results Analysis

3.1 Estimation of Kilometers Saved Through MKD

Based on survey results, a first estimate of the kilometers that can be moved from single round-based trips for grocery shopping to MKD routes is hereafter proposed considering the trips currently made by car, in order to understand if MKD can help in reducing travelled distances and related externalities.

The adopted procedure works as follows:

1. The number of users making their grocery shopping by car (g) is estimated:

$$n_{car}^{g} = \frac{N_{car}^{g}}{N^{g}} \cdot 100 \tag{1}$$

   where N_{car}^{g} is the number of users that stated to make grocery shopping by car during the survey, while N^{g} is the total number of users that makes grocery shopping;
2. As highlighted in the previous paragraph, those who use cars are more likely to going to supermarkets and large-scale retail trade centers s ($n_{car}^{g,s} = \alpha^{s|car} n_{car}^{g}$), where $\alpha^{s|car}$ is the survey share of users going to supermarket; thus, $n_{car}^{g,s}$ is divided according to revealed travelled distances (the distances are investigated in the survey according to specific classes $c^{d|type}$ that are a function of the *type* of shop reached; for supermarket and large scale retail trade centers, classes can be seen in Table 4, where the median value is adopted for each class, except for the last one where a value of 5.5 km is assumed):

$$n_{car,c^{d|s}}^{g,s} = \alpha^{c^{d|s}} n_{car}^{g,s} \; \forall \, c^{d|s} \tag{2}$$

3. For each distance class, users interested in adopting MKD services are computed:

$$n_{car,c^{d|s}}^{g,s,MKD} = \alpha^{MKD|c^{d|s}} n_{car,c^{d|s}}^{g,s} \; \forall c^{d|s} \tag{3}$$

4. The average weekly frequency $f_{car,c^{d|s}}^{g,s,MKD}$ of grocery shopping of users belonging to each distance class and joining MKD services is computed;
5. The kilometers traveled by car per week to carry out grocery shopping (round trips) are estimated as:

$$km_{car}^{g,s,MKD} = 2 \sum\nolimits_{c^{d|s}} n_{car,c^{d|s}}^{g,s,MKD} \cdot \overline{c}^{d|s} \cdot f_{car,c^{d|s}}^{g,s,MKD} \tag{4}$$

6. The kilometers of point 5. Are scaled based on different assumptions on the frequency related to the adoption of MKD, thus computing the kilometers that can be moved from round-based trips to MKD routes.

Points from 2. to 5. Are repeated for those who move for grocery shopping by car but adopting a mixed behavior: i.e. those users who revealed to visit both supermarkets and small retail stores. In such a case, since the survey did not collect the weekly frequency

Table 4. Distances investigated in the survey as a function of shop type

Supermarket or Large-Scale Retail trades	d < 1 km	1 km ≤ d < 3 km	3 km ≤ d < 5 km	d ≥ 5 km
$\bar{c}^{d\,|s}$	500 m	2 km	4 km	5.5 km
Small retail stores or food markets	d < 0.5 km	0.5 km ≤ d < 1 km	1 km ≤ d < 2 km	d ≥ 2 km
$\bar{c}^{d\,|srs}$	250 m	750 m	1.5 km	2.5 km

differentiating between the two different shop types, two extreme assumptions have been made:

Hp1: a unit weekly frequency is associated to the supermarket, while the remaining fractional share of the weekly frequency is associated to small retail stores; in such a case, the obtained kilometers $km_{car}^{g,mixed-Hp1,MKD}$ are an overestimation of round-based trips since it is assumed a higher frequency for the supermarket which implies higher travelled distances.

Hp2: a unit weekly frequency is associated to small retail stores, while the remaining fractional share of the weekly frequency is associated to supermarket; in such a case, the obtained kilometers $km_{car}^{g,mixed-Hp2,MKD}$ are an underestimation of round-based trips since it is assumed a higher frequency for small retail stores which implies lower travelled distances.

At the end, a range of travelled distances can be computed (Table 5) combining both users moving by car to supermarkets and users moving by car considering the two mixed options (supermarkets and small retail stores).

A similar approach can be found in Gonzalez Felieu et al. [15] that proposed a substitution procedure for estimating number of trips and corresponding travelled distances for shopping drive, home delivery and reception points' strategies. Among all the scenario simulated, they found that the joint usage of home deliveries and proximity reception points the most realistic combination which results in a reduction of around 13% of road occupancy rates in urban areas.

Table 5. Computation of km travelled by car per week: round-based trips for grocery shopping every 100 households

kilometers traveled by car per week to carry out grocery shopping [km/100 households]		
$km_{car}^{g,s,MKD}$	$km_{car}^{g,s,MKD} + km_{car}^{g,mixed-Hp2,MKD}$	$km_{car}^{g,s,MKD} + km_{car}^{g,mixed-Hp1,MKD}$
164	188	207

According to point 6., and given the kilometers computed in Table 5, it is possible to derive the kilometers that can be moved from round-based trips to MKD routes (Table 6). Finally, an estimation of possible reduction in emissions of CO is conducted

adopting the kilometers per week moved from round-based trips to MKD routes and considering the MKD service provided through electric vehicles such as cargo bikes; thus, CO emissions can be considered proportional to the kilometers moved to MKD, according to the average emission factor for passenger cars provided by ISPRA [16].

Table 6. Estimation of km moved to MKD and related reduction of externalities

		km per week moved from round-based trips to MKD [km/100 households]		
MKD adoption behavior	MKD adoption frequency [times/month]	$km_{car}^{g,s,MKD}$	$km_{car}^{g,s,MKD} + km_{car}^{g,mixed-Hp2,MKD}$	$km_{car}^{g,s,MKD} + km_{car}^{g,mixed-Hp1,MKD}$
Frequent user	8	47	54	59
Average user	4	23	27	30
Under Average user	2	12	13	15
Occasional user	1	6	7	7
		g of CO saved for each week [g/100 households]		
MKD adoption behavior	MKD adoption frequency [times/month]	$km_{car}^{g,s,MKD}$	$km_{car}^{g,s,MKD} + km_{car}^{g,mixed-Hp2,MKD}$	$km_{car}^{g,s,MKD} + km_{car}^{g,mixed-Hp1,MKD}$
Frequent user	8	20	23	25
Average user	4	10	11	12
Under Average user	2	5	6	6
Occasional user	1	2	3	3

Results, summarized in Table 6, show that the kilometers per week moved from round-based trips to MKD can range from 6 km/100 households (scenario related to MKD occasional user and minimum value of km travelled for grocery shopping) to 59 km/100 households (scenario related to MKD frequent user and maximum value of km travelled for grocery shopping); the reduction of CO emissions is equal to 2 g/100 households and 25 g/100 households, respectively.

4 The Work Ahead: Development of a Behavioral Model

The next step of this work consists in the investigation of the potential adoption of MKD through the development of a behavioural model; indeed, the behavioural model will allow to generalize the results, simply computed on the basis of the percentages derived

by the survey, while considering socio-economic factors and personal attitudes of each single user. Thus, interviews output is the basis for the development of a random utility model (RUM).

Given a study area U and a number of households N, the potential users adopting MKD service, N^{MKD}, can be forecasted as follows:

$$N^{MKD} = \sum\nolimits_{z \in U} N_z^h \cdot p_z^{MKD}\left[m(h_g|\boldsymbol{T}), \boldsymbol{sc}, \boldsymbol{at}, \boldsymbol{MKD}\right] \tag{5}$$

where

- N_z^h is the number of households living in a certain traffic zone z within the study area U;
- $p_z^{MKD}\left[m(h_g|\boldsymbol{T}), \boldsymbol{sc}, \boldsymbol{at}\right]$ is the percentage of households living in zone z with socio-economic characteristics ***sc*** (e.g. income, family size) and attitudes ***at***, usually travelling with mode m for grocery shopping, that potentially can adopt a MKD service;
- $m(h_g|\boldsymbol{T})$ is a function of the habits related to grocery shopping, primary influenced by travel costs expressed as a vector $\boldsymbol{T}$;
- ***MKD*** is a vector that correlates MKD subscription conditions (e.g. cost of each order, minimum order, shipping cost)

Within RUMs family, logit one is the model type chosen for the analysis [17]. Logit models propose the simplest formulation based on the fundamental hypothesis of user rationality (i.e. user chooses the alternative with the maximum perceived utility). The utility U for each alternative j belonging to the set of alternatives J for the user i is composed by a systematic element V and a stochastic error ε:

$$U_i^j = V_i^j + \varepsilon_i^j \; \forall j \in J \tag{6}$$

Logit model assumes that the random elements ε_i^j are distributed independently and identically as a Gumbel distribution with a parameter ϑ. This hypothesis allows the computation of the probability of choice, p_i^j, as follows:

$$p_i^j = \frac{e^{V_i^j/\vartheta}}{\Sigma_{j' \in J^e} e^{V_i^{j'}/\vartheta}} \; \forall j \in J \tag{7}$$

The systematic utility component V_i can be expressed as a linear combination of the attributes X_k through their relative coefficients β_k and an additional coefficient ASC (alternative specific constant) which represents all the factors not expressed through the parameters:

$$V_i^j = \left(\Sigma_k \beta_k * X_{i,k}^j\right) + ASC^j \tag{8}$$

$$\ln L(\beta, \vartheta) = \Sigma_i \ln p^{j'}(i)\left(V_i^{j'}\left(X_{i,k}^{j'}, \beta\right)\vartheta\right) \tag{9}$$

In the case of MKD adoption, the logit model can be easily formulated as a binomial model where the alternatives are: 1) subscribe a MKD service; 2) not subscribe an MKD service. In such a case, the alternative 2) is equal to zero, while all attributes X_k are included in the systematic utility.

The calibration of the behavioural model in (5) is currently ongoing: preliminary results showed as socio-economic characteristics ***sc*** influencing the choice are the age of the family member who usually does the shopping for grocery and the household income; instead, statistically significant attitudes ***at*** are the importance toward the time saving and the avoidance in food waste.

5 Conclusions

The online survey conducted provided some important indications, highlighting that some specific attitudes and habits have a greater impact on the choice to join MKD services, as well as age and propensity towards technology and social media play an important role. The analysis highlighted the importance for users to optimize time, travel and costs for shopping, but at the same time showed a certain attention for aspects such as food waste reduction and healthy foods preference.

Based on the information obtained from the survey, the potential reduction in trips (i.e. km travelled) for grocery was estimated (i.e. km moved from single car trip to MKD routes) along with the related reduction of externalities. Results show the potential of save approximately 60 km per week for every 100 households if the use of MKD services became frequent. The related environmental benefits in terms of pollutant emissions could be equally important, as demonstrated by the calculation of the CO reduction if only electric vehicles were used for MKD services.

In the end, a behavioral model (logit model) to generalize the results of the survey and reliably predict the willingness to use a MKD service is proposed as a function of socio-economic factors and personal attitudes. Future works will focus on the calibration, and subsequent validation, of the behavioral model, as well as the check and possible generalization of the results considering larger sample data.

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Experimentation on Risk Reduction by Training: A Framework for Seminar Activity

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Abstract. Every year, at the global level, disasters connected to natural and anthropic events produce relevant losses. This implies the necessity to plan, design and implement a system of actions for reducing risk and their components (occurrence, vulnerability and exposure). This paper focuses on the exposure component, by considering the training actions aimed at improving the community's preparedness for evacuation procedures deriving from the emergency planning process. By selecting the discussion–based training class, this paper presents a framework of a seminar, that is the simplest action aimed at orienting participants about the planned indications. The framework is inspired by the US standard approach to training actions. The structured seminar can be considered the first step of a wide training cycle that includes discussion and operation-based exercises. An example of a seminar is clear in the air transport sector. The seminar has become standard practice regulated by ICAO for defining procedures to follow in the event of danger on aircraft. The procedure is aimed at increasing awareness and it requires competency of operators. So, the entire cycle of a seminar must contribute to risk reduction by increasing awareness of the procedures provided and their testing in a stress-free environment. The entire cycle contributes to risk reduction by increasing awareness about planned procedures and their experimentation in a no-stress environment. Training and exercises constitute an opportunity to reduce risk and then the potential damages produced by disasters. Seminars are low-cost activities aimed at putting into practice the planned evacuation procedures. The paper is useful for decision-makers and takers involved in emergency planning procedures who want to increase the effectiveness of preparedness actions implemented before an emergency event.

Keywords: Disaster risk · Exposure · evacuation planning · training and exercises · seminars

1 Introduction

The increasing number and complexity of environmental and man-made threats require a prepared and coordinated community response. In this context, emergency planning, with a specific focus on evacuation procedures, plays a crucial role in reducing risks, particularly the exposure component.

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The 2030 Agenda's Sustainable Development Goals (SDGs) 1, 3 and 13 address risk reduction in three dimensions: the fight against poverty, the safety and resilience of cities and communities, and the fight against climate change [1]. According to the Agenda 2030, the 'Sendai Framework for Disaster Risk Reduction 2015 – 2030', promotes a global action plan that commits all subscriber countries to out-line a globally shared strategy, establishing seven general goals and four action priorities, to achieve a substantial reduction in disaster risk and loss of life. In particular, "Priority 1: Understanding disaster risk" promotes dialogue and cooperation between the scientific communities and decision-makers for sharing training programmes aimed at improving knowledge and understanding of existing risk reduction practices [2].

Literature indicates that planning initiatives to reduce risk and in particular exposure components through evacuations, are not homogenous among all countries [3]. An example is the difference between the United States (US) and European Union (EU) approaches. In the US, state and local federal agencies manage emergency planning and mitigation of natural and man-made hazards, with a specific focus on actions planned and implemented before an emergency event. This is connected to the disastrous events (e.g. the terrorist attack on the Twin Towers) that occurred at the beginning of the new millennium. These events underlined the necessity to increase the level of community preparedness for evacuation procedures as a fundamental strategy for reducing human losses [4]. In this context, the Federal Emergency Management Agency (FEMA) established the Homeland Security Exercise and Evaluation Program (HSEEP), a framework for planning, conducting, evaluating and improving exercises to define a common approach and improve national preparedness [5].

In case of a disaster within the European Union, all Member States and the 10 Participating States can ask the 'EU Civil Protection Mechanism' for assistance by communicating directly with the Emergency Response Coordination Centre (ERCC). The mechanism was launched in 2010 by the Directorate-General for Civil Protection and Humanitarian Aid Operations (DG ECHO) [6]. In short, while the EU focuses primarily on consequence management after the event has occurred, in the US, actions begin before the event occurs. In addition to this, in the EU there is a lack of standardised emergency management procedures requiring Member States to test emergency plans following a systematic cycle of exercises. In any case, there is a need to bridge the gap between planning actions and their implementation during emergencies. Training and exercises play a relevant role in bridging this gap. This research focuses on evacuation planning for reducing exposure risk components. The integrated adoption of Transport System Models (TSMs) [7], for evaluating ex-ante evacuation planning effects, with training exercises actions, for bridging the recalled gap, constitute the challenges of this research.

In this context, the specific research contributions of this paper regard:

- the investigation of the role of training and exercise actions to increase the level of preparedness;
- the presentation of a seminar framework starting from consolidated approaches toward the possibility of adopting TSM for evaluating seminars' effects;
- the illustration of some examples of seminars implemented.

In line with this research's contribution, after this introduction, the paper has four sections. Section 2 illustrates the main elements of actions of a planning process aimed at increasing preparedness, inside the entire cycle of risk management. Specific attention is on the seminar exercises. Section 3 describes the proposed seminar framework enhanced with the support of TSM. Section 4 reports some empirical evidence of seminars implemented at the global level. Section 5 closes the paper with a discussion and some final remarks.

2 The Role of Training and Exercises in the Preparedness Phase

2.1 Planned Actions for Increasing Preparedness

Risk reduction is the main objective of all phases constituting the entire disaster management cycle (preparedness, mitigation, response, recovery) [8]. This paper focuses on the preparedness phase. It comprehends all actions that can be implemented before the disaster event occurrence. This phase includes actions aimed at increasing awareness about the disaster's characteristics and defining how to face the potential consequences. As far as the exposure risk component, preparedness activities include models and methods for performing safe and effective evacuation procedures [9]. For this reason, the authorities, community at large, specific groups (e.g. households) and individuals need to be ready. Then the preparedness phase must plan the actions that must be taken when a disaster occurs [10]. By referring to an evacuation plan, different hierarchical levels are proposed for which preparedness actions can be specified. The information contained in the plan is transferred from top to bottom using different approaches. The content of the information is also adapted to the hierarchical level referred to (Fig. 1).

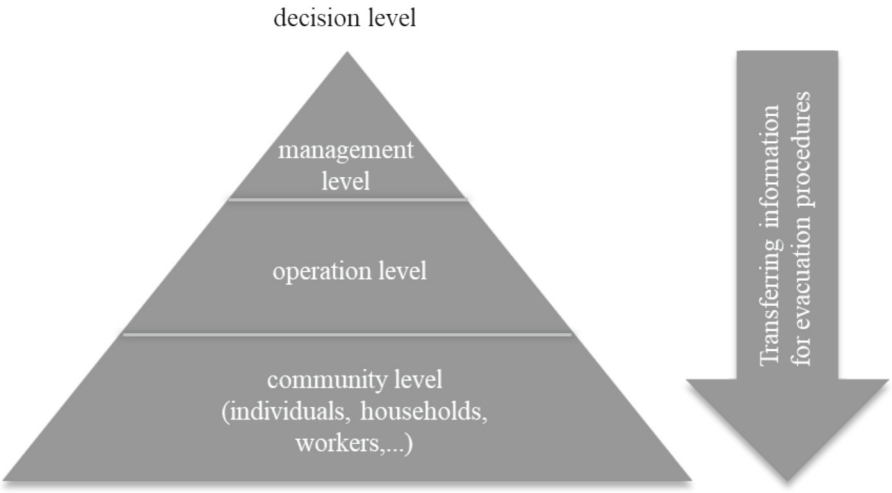

Fig. 1. Preparedness actions for different hierarchical levels.

- decision level, including decision makers that define planned actions and decision takers that adopt the planned configuration of a transport system in an evacuation condition [11];
- management level, including coordinators that implement planned actions and evacuation procedures;
- operation level, including emergency operators (e.g. civil protection volunteers) that provide aid and assistance in emergencies;
- community level, including population and subgroups (e.g. individuals, families, workers) moving from emergency areas to safe areas.

It is necessary to fill the gaps and distances between all hierarchical levels to increase the effectiveness of the planned actions during emergencies. Therefore, it is necessary to transfer the information and instructions about planned procedures (e.g. evacuation paths) from the decision-making level to the entire community.

2.2 Training and Exercises Actions

Training and exercise actions increase preparedness. The main aim is to fill the gap mentioned in Sect. 2.1. Furthermore, recent literature underlines the role of training and exercises in risk reduction [12]. The only redaction of an emergency plan process does not provide the expected outcomes. By performing training and exercise it is possible to experiment in a stress-free environment with the planned action to verify possible lacks (e.g. resources), for instance in terms of accessibility to local public transport services [13], and improving procedures. Training and exercise activities contribute to increasing the awareness of managers, operators and those involved during the emergency. The specific aim is to diffuse the information contained in the plan so that people are aware of the procedures set out in the plan. The general objective is to reduce the risk because the increase in awareness helps to increase the readiness of all those involved so that they can implement the planned procedures effectively. It should be considered that the effects on awareness of actions to be taken in the event of an emergency are not continuous over time but tend to diminish gradually. Actions should be planned on a cyclical basis. This contributes to reducing the exposure component of the risk ([3, 14]).

Literature groups training and exercises actions in two classes [5] (Fig. 2):

- discussion-based exercises, including seminars, workshops, Table Top Exercises (TTE) and games aimed at familiarizing with the planned evacuation procedures;
- operation-based exercises, including drills, Functional Exercises (FE); Full-Scale Exercises (FSE) to simulate, in an operational context, real evacuation procedures to be implemented in an emergency real situation.

The classification implies an increasing level of:

- complexity, in terms of involved subjects and simulated operations;
- capability, in terms of available human and material resources for achieving outcomes (e.g., reducing evacuation times) under specific conditions.

The first class of actions includes low-cost simulation activities aimed at reviewing and developing plans. The second class of actions includes simulated activities performed

in a more realistic environment involving stakeholders for testing emergency plans. It is possible to perform the exercises in a 'building block', or a sequence consisting of only two or more exercises belonging to different classes. An example is a sequence constituted by a seminar, followed by a TTE that evolves in an FSE.

This paper focuses on the seminar which is the first and simplest exercise. Section 3 presents the main characteristics of a seminar.

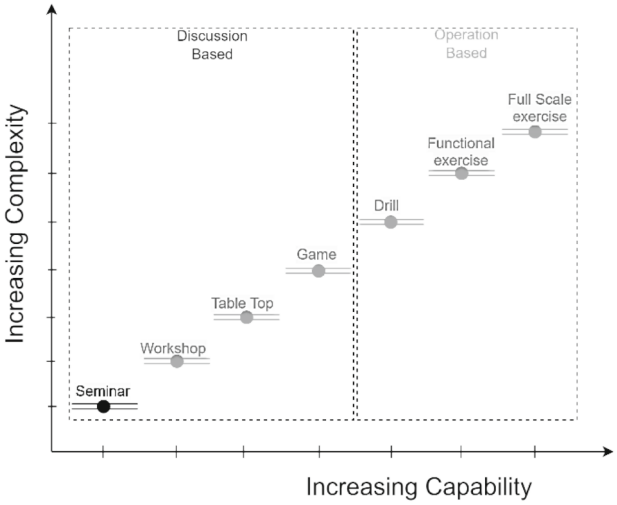

Fig. 2. Exercise classes.

3 The Seminar Framework

The seminar is an efficient tool to improve people's ability to carry out the preparation actions outlined in the plan on time. Through frontal lessons conducted by qualified staff, the seminar contributes to filling information gaps related to risks, providing a solid basis for awareness about planned actions. The activity is based on informal discussion about the contents of the emergency plan to familiarise participants with the planned procedures. Communication between the presenter and the participants is unidirectional (Fig. 3). The presenter explains the contents of the emergency plan to an audience consisting of a small but select group of key stakeholders, including industry experts, practitioners and community representatives. The activities are 'lecture-based' and involve the detailed presentation of the plan and its procedures.

The proposed framework is coherent with the international emergency exercises. In the consolidated approach, the seminar design is aimed at defining its contents according to the evacuation planning. In line with the paper's objectives, the proposed framework is enriched with a set of TSM applied to simulate the evacuation of people, by considering the effects produced by the information provided to users by the seminar (Sect. 3.1).



Fig. 3. Schematic representation of seminar exercise.

Then the seminar is conducted and evaluated by adopting a circular "Plan-Do-Check-Act" sequence (Sect. 3.2). A set of indicators measures the expected exposure reduction providing support for decision-makers to improve evacuation planning (Sect. 3.3).

Generally, seminars are designed, conducted and evaluated following the consolidated path. The general objective of this research concerns the possibility of following an advanced path aimed at estimating the seminar's contribution to risk reduction, with reference to the exposure component.

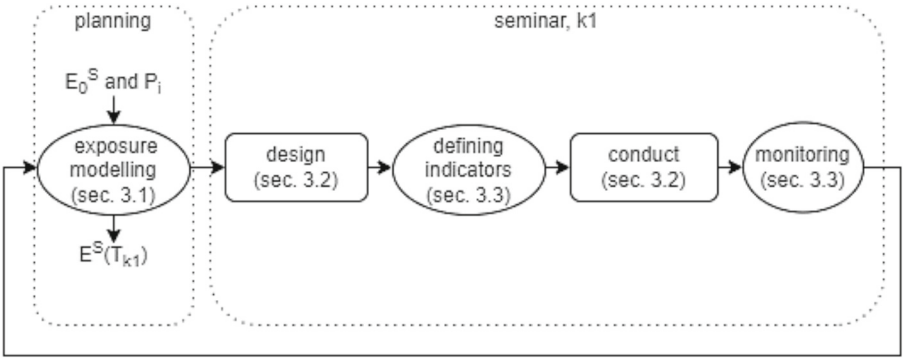

Fig. 4. Seminar framework.

3.1 Exposure Modelling

The use of simulation models such as Transport System Models (TSMs) in the urban context facilitates the quantification of exposure components for different scenarios. This allows analysts to assess the effects of the planned actions included in the evacuation plan and subsequently described in the seminar. According to Russo and Rindone [3], if P_i is the generic best plan, the maximum theoretical exposure reduction that can be achieved with the evacuation plan alone, $E(P_{min})$, represents the exposure limit level to target by performing training and exercises. Indeed, without adequate training of the users and operators involved, the plan is not sufficient to achieve the expected exposure reduction. Each training and exercise action contributes to the overall risk reduction; in particular, the impact of each action is independent of the others. This means that the exposure reduction resulting from each action can be assessed separately. Figure 5 is a graphic representation of exposure reduction obtained from the implementation of

all exercises. This paper focuses on the seminar's contribution to exposure reduction (ΔE^{S}_{k1}).

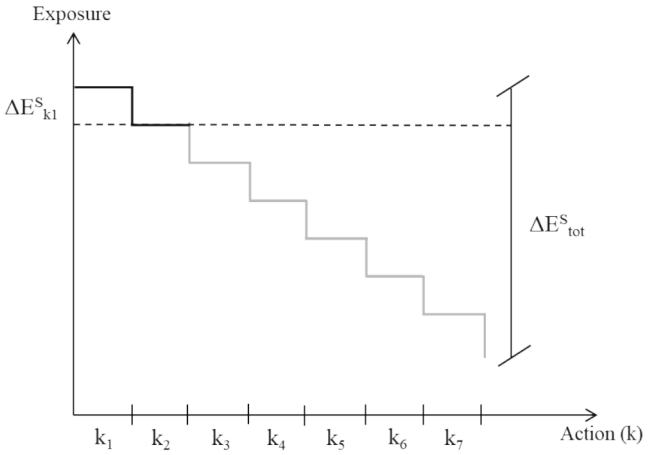

Fig. 5. Reduction of exposure levels as a function of operating classes (see Fig. 2) k_1: Seminar; k_2: Workshop; k_3: Table Top Exercise; k_4: Game; k_5: Drill; k_6: Functional Exercise; k_7: Full-Scale Exercise).

Exposure reduction resulting from the seminar can be expressed through the following equation:

$$\Delta E^{S}_{k1} = E^{S}_{0} - E^{S}(T_{k1})$$

where E_0 is the exposure value without the evacuation plan; while $E(T_{k1})$ is the exposure after implementation of the seminar, measured ex-ante through simulation models.

3.2 Design and Conduct

Seminar's Design. The seminar can be designed according to the US HSEEP guidelines. The design concerns the definition of the event that produces the emergency scenario (e.g. an imminent explosion of a tank transporting dangerous goods) and the planning contents defined for facing each emergency (e.g. evacuation procedures). The critical phases occurring in the emergency event are identified. These include a description of the nature of the emergency; the area and the population involved; and the planned responses of local authorities, non-governmental organisations and other entities during the phases of the event. The key factors should be described following the temporal dynamics of the specific emergency event, from the start time to a possible conclusion.

The output of this step constitutes the exercise material containing the above characteristics. The material comprehends documents of the exclusive use of exercise planners, facilitators, evaluators and other material useful for players. For instance, the guide of a seminar can be a Situation Manual (SitMan) that provides exercise participants with the tools to perform their roles in the exercise.

Seminar's Conduct. According to the designed characteristics, the seminar is conducted involving the presenter and different classes of participants. During the seminar specific to each emergency event, the planned actions are illustrated by the presenter to the participants (e.g. the evacuation procedures for moving people from the dangerous area to shelter areas). Intervention strategies are outlined identifying: the persons in charge of overseeing and controlling the implementation of the emergency procedures; the arrangements for requesting the intervention of the authorities in charge; the necessary information upon their arrival; the functional network of cooperation between the various territorial bodies, rescue operations, evacuation plans; the allocation of available resources such as emergency and logistical infrastructure.

3.3 Evaluation

To assess the level of exposure, it is necessary to consider the variables that may differ based on the context and type of emergency. The variables are defined before the seminar is conducted. Upon conclusion of the seminar, the evaluator has the assignment of monitoring the previously defined variables.

Variables Definition. Evaluation of the exposure reduction can be performed by adopting different kinds of indicators. A first attempt is to measure this contribution to the quantity and quality of the scheduled seminars.

For each hierarchical level of disaster management, a common indicator for assessing exposure reduction can be defined. By concerning a specific emergency scenario (s), the indicator is defined as follows ([15]):

$e^s{}_{sem}$ = *time needed for the individual to acquire the plan documentation*

The indicator measures the "capability", by evaluating the exposure reduction, and "complexity" by quantifying the number of actors involved. In particular, this indicator can be scaled up according to the number of seminar participants. Then the following specified indicators are proposed with reference to:

- The groups belonging to the decision levels introduced in Sect. 2.1 (m: managers; o: operators; c: people community) and belonging to Fig. 1;
- The organisational characteristics of the seminar in terms of
  - temporal length, or seminar duration (h) (e.g. 3 h),
  - frequency, or number of seminars to be held (k_1) in a time interval (t) (e.g. one seminar per year),
  - and human resources;
- Number of seminar participants (n_p), which measures the maximum number to whom the seminar lecture can be addressed.

Indicators can also be specified with reference to the different emergency scenarios (s) for which the plan was developed.

A greater number of participants at the different hierarchical levels, together with the correct organisation and implementation of the seminar, has a positive effect in terms of

Table 1. Indicators for seminar planning.

Hierarchical level	n. of participants	Temporal length	Frequency	Human Resources
Management level	$n^m{}_p$	h^m	$k_1{}^m$ /t	$n^m{}_p$
Operation level	$n^o{}_p$	h^o	$k_1{}^o$ /t	$n^m{}_p/n^o{}_p$
Community level	$n^c{}_p$	h^c	$k_1{}^c$ /t	$n^o{}_p/n^c{}_p$

increased diffusion and awareness of the indications contained in the plan. This helps to reduce the value of the indicator used to measure ex-ante and ex-post exposure reduction (e_m).

Monitoring. Monitoring consists of measuring the variables defined before the conduct of the seminar, this phase can be carried out in different ways.

An immediate way that can be used to monitor a seminar exercise, is to check that the evacuation plan has been received by all the actors involved. A more complex procedure is direct observation by the evaluator. During the seminar, the evaluator, through the drafting of a document, collects quantitative data related to the indicators defined previously.

4 Test Cases

4.1 Example of Modelling

The United States has adopted a planning model based on 'capabilities' with reference to the emergency management capacities of the agencies involved. The assessment of this capability is part of the THIRA (National Threat and Hazard Identification and Risk Assessment) process, organised in three phases identified with the following questions: "1) How prepared is the Nation? 2) What preparedness gaps does the Nation face? and 3) What strategies does the Nation need to develop to address those gaps?". To achieve the goals outlined in THIRA, FEMA developed the National Risk and Capability Assessment (NRCA), which brings together a suite of assessment products to measure risk and capability across the nation through a standardised process [16]. In parallel, FEMA introduced the National Stakeholder Preparedness Review (National SPR), a tool that can measure the current capability level and thus the distance to capability goals defined in contingency plans. Together, these tools make it possible to define and measure gaps at the national level [17].

According to US experiences about THIRA Fig. 6 (a) shows the contribution of training actions performed before a disaster event. The expected results are to increase the capability to deal the emergencies. According to Russo and Rindone [3], the exposure component of risk is related to the quantity and quality of training actions. More training over time leads to greater awareness of the actions to be taken (capability) in the event of various risk situations. Then Fig. 6 (b) represents the contribution of the implementation

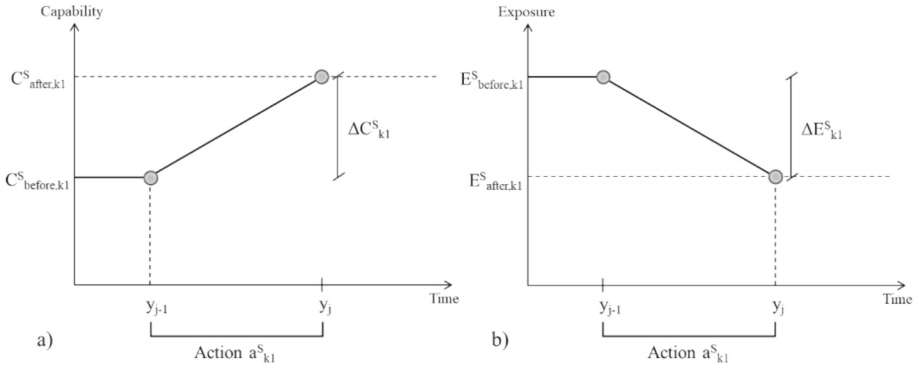

Fig. 6. Comparison of Capability (a) and Exposure (b) as a function of training time. The 'Action' time interval represents the time spent on training actions (in this case seminar).

of training and exercise actions before a disaster event. Generic event (S). One of the potential effects of capability enhancement is exposure reduction.

In each capability target, a critical task is described, which is the one listed in the emergency plan developed by the planner; the ability to perform critical tasks is an indicator of preparedness. In addition, each target consists of standardised impact metrics, which represent the main quantifiable consequences associated with the threat, and a timeframe metric, which defines the time interval in which the action must be performed. In the case of evacuation, Fig. 7 shows an example of a critical task using the THIRA capability target as a reference:

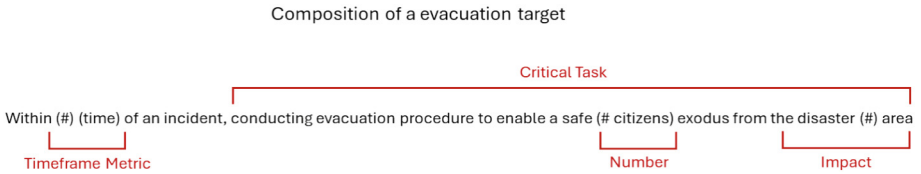

Fig. 7. Example of a capability target (Adapted from [17]).

The literature review reveals a limited use of TSM to simulate and evaluate the effects of a seminar in terms of exposure reduction.

4.2 Examples of Design and Conducted Seminars

Some studies emphasise the importance of promoting training courses and emergency drills to increase community awareness and resilience. At the same time, there is a communication gap between experts and citizens that includes not only sharing information but also assessing the understanding of the content of information [18]. In Italy, communication between institutions and citizens mainly concerns the immediate post-disaster phases. Other international examples, however, promote emergency preparedness through local events. For example, Australia, Canada or Nepal provide citizens

with emergency kits and updated guidelines [19]. In the study carried out by Hoffmann and Muttarak [20], the importance of psychosocial factors in disaster preparedness, in addition to socio-demographic characteristics and structural/geographical variables, is highlighted in the low- and middle-income countries of Southeast Asia. Increased awareness of hazards and risk perception increases people's ability to implement the actions foreseen in the plans.

In some contexts, seminars are usually used with internationally standardized procedures.

It should be considered that the discipline governing safety in the workplace includes obligatory training and refresher courses. For example, in Europe, the Framework Directive 89/391 on the Safety and Health of Workers (OSH) lays down general principles on the prevention of risks at work, including planning and managing evacuation in case of emergency. The guidelines of the Framework Directive set minimum safety requirements and do not include specific details on the procedures to be performed, which can be supplemented by individual EU member states. In Italy, D.Lgs. 81/08 [21] provides for the mandatory drafting of the Emergency and Evacuation Plan (EEP). The planning and implementation of the EEP is the responsibility of the Employer in cooperation with the Prevention and Protection Service Manager (RSPP), who is obliged to attend a training course and a refresher course every 5 years. Mandatory training in this case only ends at the management level.

In some transport systems, seminars are already common practice.

An example of a seminar implemented on a high-frequency basis concerns the air transport sector. Reference is made to the safety briefing provided by flight personnel to passengers before take-off. The pre-flight briefing is a requirement established by the national civil aviation authority (for Italy ENAC) under the recommendation of the International Civil Aviation Organisation [22] which provides a specific training course on aircraft landing and emergency evacuation procedures for cabin crew (ICAO training). The way airlines choose to carry out the briefing depends on the company's internal policies: safety information can be pre-recorded or provided live. A live demonstration involves a flight attendant standing in the aisle while another attendant explains the procedures to be implemented.

Another example of a seminar is the one that takes place on ships established by European Regulation No. 1177 of 2010 on passenger rights [23]. In this case, information is provided to passengers in the form of recorded audio. A special case is the Cruise Ship. According to the International Convention for the Safety of Life at Sea (SOLAS) [24] dictates, safety instructions are provided to passengers before departure in the form of a seminar combined with an evacuation exercise.

4.3 Examples of Evaluation

As far as concerns Table 1, the application of the indicators in the training context of the RSPP figure is shown below (Table 2):

Table 2. Indicators for planning a RSPP training seminar.

Hierarchical level	n. of participants	Temporal Length	Frequency	Human resources
Management level		100	5	

Considering the known references for seminars used in the aeronautical field, we have assumed the application of the indicators proposed in Table 1 in a scheduled flight context (Table 3):

Table 3. Indicators for planning a seminar for scheduled flights.

Hierarchical level	n. of participants	Temporal length	Frequency	Human resources
Operation level	20	95	-	1
Community level	180	0.17	1/flight	3

We considered an average number of passengers of about 180 (Boeing 737–800 or Airbus A320), three flight attendants and a seminar time of about 10 min for the level of passenger training. The flight crew training data were obtained from [25]. Considering the method by which the seminars are conducted (e.g. frequency), a significant contribution to reducing exposure can be expected, considering also that evacuation instructions in the event of an emergency are always available to passengers. Therefore, the value of indicator e_m is limited.

5 Discussion and Final Remarks

In some sectors, the seminar is a standard practice already adopted. This is the case, for example, of air transport. Before the departure of an aircraft, the standard procedure requires the on-board staff to inform the passengers on board about the procedures to be adopted in the event of an emergency. The objective is to increase the passengers' awareness about the actions to be taken in the event of a plane crash. This type of seminar contributes significantly to the reduction of exposure.

The same type of exercise is not common in civilian systems. European legislation on civil protection establishes the procedures but does not require the carrying out of exercises. However, the seminar form is the easiest to design and implement. Repetition of the same exercise (e.g. a seminar) helps to increase awareness of procedures, and errors and improve elements. Instead, the increase in complexity of an exercise allows people to increase their ability to respond to an emergency event. At the same time, it is necessary to adopt a TSM approach to simulate the effectiveness of actions, before their implementation. In this case model simulations and exercise simulations should be integrated. Mutual interchanges must be generated between the two simulation activities

to increase knowledge of the phenomenon. The real phenomenon occurs with a very low frequency and is therefore difficult to observe directly. However, the exercises are a tool to approximate reality, even if some conditions (e.g. panic) are difficult to reproduce.

This research can have further developments in different directions.

The first direction concerns the models' accuracy in simulating the transport system in evacuation conditions. It is possible to use ICT technologies to acquire information to better understand the phenomenon. Greater integration between ICT technologies and TSM models is needed to offer support and reliable tools to decision-makers.

A second direction concerns the ability to carry out and observe the exercises. Existing methods for evaluating exercises can be supported by TSM. Also, in this case, it is necessary to adapt ICT solutions integrated with the TSMs to support the carrying out of the exercises.

The third direction concerns the estimation of the risk reduction connected to the adoption of the models and exercises. It is necessary to build models for estimating the contribution of each training and exercise activity to risk reduction. These quantifications require more insights. For instance, efficacy must also be assessed in relation to people's actual behaviour in an emergency; not only in terms of output but also in terms of outcomes [9].

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Building Multi-dimensional Models for Assessing Complex Environmental Systems (MES 2024)

Supporting the Planning Management of UNESCO Sites: A Literature Review Between Urban Showcase and Gentrification

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Abstract. Fostering tourism with UNESCO World Heritage sites needs to address sustainability by balancing the preservation of cultural heritage, local economic growth, and tourism enhancement. Despite tourism is one of the sectors of the economy which can increase economic attractiveness, with benefits on local employment, real estate prices, or social capital, it could also increase costs sustained by cities and territories, require to adapt their system's rules to a different entity of flows, manage and avoid the risk of gentrification and displacement of local residents. Within this context, the present contribution examines the complex dynamics behind sustainable tourism management with particular reference to UNESCO World Heritage sites. This research work develops a literature review presented through the PRISMA approach (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to deliver to public bodies a synthesis of the relevant scientific documents to identify a set of multidimensional assessment tools for achieving a sustainable tourism planning in their contexts. The outputs may be of decision-aiding utility for local public bodies, urban planners, and local communities to balance tourism management with heritage preservation and social well-being. This paper contributes to the ongoing debate on sustainable tourism management and planning in urban contexts by highlighting the UNESCO challenges and proposing a systematic approach to assess and manage tourism. The relevance of adopting a multidimensional approach may contribute to envisioning winning strategies for safeguarding cultural assets and urban development.

Keywords: UNESCO · Sustainable tourism · Strategic assessment · Gentrification · Literature analysis

1 Introduction

Tourism is recognized to be one of the cornerstones of the economy of a country, even if it was born as a niche travelling practice (i.e. *grand tour*) for business, aesthetic, or educational purposes, ranging from visiting Greek classical artefacts to Mediterranean

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culture or exotic landscapes, among others. With the progressive industrialization and globalization of our planet, this practice was opened to the whole society. Therefore, tourism demand and tourism accommodation supply became widely available over time and well-linked with the world such as via railways, cruise ships, or airplanes.

In the previous century, urban and territorial marketing founded in tourism as one of the major driving forces for sustainable local development, by capturing financial resources (e.g. EU INTERREG – European Interregional funds, EU FESR – European Funds for Rural Development), with direct and indirect effects on cultural and natural heritage, and urban and territorial criticalities as well (e.g. abandonment of inner and rural areas, seasonal employment, or facilities and accommodation availability) [1]. Even if some places are recognized as tourism destinations thanks also to their initial geomorphological and weather conditions, this badge is even more revealing a double-edged sword due to interdependent factors: the negative impact of high tourism flows on the environment (from garbage to illegal urbanization of water-edge) is closely related to the progressive lowering quality of tourism experience and local residents' dissatisfaction (or rather who cannot gather any profitability by imbalanced and massive tourism arrives) [2].

In a few words, we are assisting a mixture of bad and good practices which foster obstacles and opportunities for sustainable development at the same time. The landscape is further difficult when a UNESCO World Heritage site is present within a tourist destination. In some cases, cultural heritage and landscape become showcases for tourists and the remaining city could risk being gentrified, leading to some positive implications, such as the regeneration of decaying or down-grounded parts of the city [3], but mostly negative implications, compromising community welfare and historical preservation [4, 5]. In some other cases, the presence of UNESCO can lead to enriching multi-cultural values, and economic prosperity, thus aiding in the conservation of the Outstanding Universal Value (OUV) [6].

While the UNESCO designation confers worldwide recognition, if public administration is not ready, this benefit could bring more vulnerability than expected. In light of this scenario, multidimensional assessment approaches are crucial for determining the sustainability of tourism planning and management, requiring a winning strategy capable of mirroring all the interests of actors and stakeholders involved in the process [7–13].This research work aims to enhance and stimulate the current debate on sustainable tourism planning and management in UNESCO World Heritage cities by focusing on a systematic literature review, using the database Scopus and presenting the procedure to the PRISMA approach (Preferred Reporting Items for Systematic Reviews and Meta-Analyses[1]) [14]. The literature aims to favor useful insights, identify the most widely used evaluation methods, and monitor sustainable tourism development trajectories by conducting a systematic synthesis of both academic literature and empirical evidence. Indeed, the research focuses on a broad view of the relationship between gentrification and WHL nomination, detailing it through the analysis of several specific case studies. The outputs are addressed to public bodies and local stakeholders and aim to provide

[1] www.prisma-statement.org *(last access march 2024).*

urban planners, technicians, tourism specialists, and local communities the tools necessary to counterbalance the over-tourism promotion of cities and territories with social welfare and tangible and intangible heritage preservation for the next generations [15].

After this introduction, the paper is structured as follows: Sect. 2 focuses on the positive and negative features of UNESCO inscription, Sect. 3 explains the methodology that founds the literature review using the PRISMA approach, Sect. 4 discusses the main findings and provides subsequently some final remarks and future steps of this ongoing research.

2 Positive and Negative Aspects of UNESCO Inscription

To promote cross-cultural awareness of culture and nature, the United Nations (UN) regularly identifies some exceptional and valuable elements to be included in the prestigious and highly recognized list of World Heritage [7]. Currently, 1199 properties are inscribed in the list, of which 933 are cultural, 227 natural and 39 mixed [16]. Recognition in the World Heritage List (WHL) is beneficial for the good inscribed, which could find solutions before a deterioration, for its conservation and promotion. Additionally, the place hosting the valuable element can benefit from it from several points of view, such as social cohesion and inclusion, education, environmental awareness, cultural significance, new jobs and services for the community, tourism opportunities and economic growth [17, 18].

Sites that have been nominated for inclusion on the list must maintain and safeguard their OUV for both the current and future generations [7, 19]. However, given the complexity of today's world, many variables can impact these valuable elements, and the various values at stake, spanning tangible, intangible, ecological, cultural and social values [20]. Firstly, climate change, natural disasters and, more in general, anthropogenic activities produce many threats to UNESCO WHL goods, such as the interaction of pollutants with materials leading to artworks and materials degradation and damages [21], biocultural landscape losses and hazard risks [22], as well as extremes of heat, fire weather conditions, heavy rainfall days, changes in mean sea level and aridity with a direct effect on the OUV of the good [23]. Secondly, unprepared public administrations and financial restrictions may cause greater vulnerability, due to a lack of practice in "good governance principles" characterized by openness, participation, accountability, effectiveness, coherence and subsidiarity to assure the successful implementation of public policies, efficient and effective allocation of public resources and to increase citizen's direct participation, involvement, engagement and empowerment [24]. Thirdly, wars and conflicts could provoke a fragile state of conservation of monuments, habitats and landscapes due to abandonment and military action [25]. Fourthly, the increase of infrastructure and specialized services to serve the nominated place could compromise traditional landscape, local specificities and views, as well as local economies. Fifthly, and partially connected to the previous impact, it is related to the negative outcomes on the local population and community, due to the spread of second-houses, Airbnb and displacement of residents (i.e., gentrification) due to the phenomenon of over-tourism [22]. In some cases, this type of problem can be caused by inefficient planning documents, which are too general or focused on a single issue without an overall view.

The relationship between planning and tourism development is complex and needs an integration of the top-down view- for the regulatory planning of tourism development - with the bottom-up view - for the inclusion of the social component at the local level [26].

Particularly for some of these reasons, UNESCO has realized the List of World Heritage in Danger. The list aims to inform the international community of conditions which threaten the very characteristics for which a property was inscribed on the WHL and to encourage corrective actions [25]. Some examples of goods included in this list, recalling the vulnerabilities previously mentioned, are listed here: the Bamiyan Valley in Afghanistan where the property is in a fragile state of conservation considering that it has suffered from abandonment, military action and dynamite explosions [25]; the middle of Vienna is consider in danger due to high-rise projects realized, that adversely impact the OUV of the site [27]; the Everglades National Park where the native plant and animal communities are extremely vulnerable to disturbance from human activities, and are threatened by agricultural and urban expansion, drainage, deliberate and accidental burning, water and air pollution, and the introduction of exotic species [28]; the Coro and its Port site in Venezuela was inscribed on the List of World Heritage in Danger in 2005 due to the unusual rains and subsequent damage to the cities of Coro and La Vela, as well as for the construction of a new beach walkway and gateway to the city, in the buffer zone, which could have a significant impact on the value of the site [29]; the Abu Mena World Heritage property is threaten by the effects of rising groundwater [30]; the Medieval Monuments in Kosovo for the absence of management and legal protection, as well as political instability [31]; Rachid Karami International Fair-Tripoli is in a precarious state of conservation, also due to a lack of funds for its maintenance [32].

Beyond the usefulness of the World Heritage in Danger list, UNESCO seems to pay little attention to the negative impacts on local populations and communities due to the spread of over-tourism, the displacement of residents, the proliferation of second homes, Airbnb, and the cost of buying and renting in World Heritage areas and cities. However, these phenomena have both economic and social implications, as well as in some cases also on the landscape and the environment. In this paper, we are particularly interested in gentrification, which term also embeds these negative outcomes on the local population and community.

Originally, the term gentrification was introduced in the academic field by English sociologist Ruth Glass in 1964 to describe the physical and social changes in a London neighborhood following the settlement of a new middle-class social group [33]. Over time, authors have identified different and sometimes interrelated causes of gentrification diffusion, based on social, economic and environmental processes, including retail gentrification, environmental gentrification, climate gentrification, studentification, tourism gentrification, and health care gentrification [34].

Due to the purpose of this paper, tourism gentrification is of special interest. Urban development and community change in response to the demands of wealthy tourists are prime examples of tourism-related gentrification [35]. This kind of gentrification is the growth of short-term rentals, which drives up housing costs, alters retail and service offerings, creates a transient population, and drives long-term residents out of the area

[34, 36]. Examples of tourism gentrification are analyzed in different places by authors: e.g. the city of Barcelona [] and the New Orleans' Vieux Carre (French Quarter) [35], Latin America [37], Asian Pacific region [38], South Africa [39], Mediterranean country, such as Croatia [40], Portugal [41], Spain [42].

Despite their valuable contribution, to our knowledge these papers analyze the specific relationship between their own case study and gentrification, without a comprehensive view of the phenomenon and without providing solutions to prevent it. This paper specifically fills this gap by exploring this possible relationship through a literature review.

3 Methodology

To better understand how the issue of gentrification has been studied and analyzed for UNESCO sites, in terms of its definition, the methodologies used, and the specificity of the cases analyzed, an analysis of the relevant literature is provided. The database Scopus was used to conduct the literature review between November 2023 and February 2024 and the PRISMA diagram [14, 43] to clearly report our systematic review. The literature review considered three combinations (or strings) of keywords that provided different results in terms of the number and type of documents found.

In the first case, the keywords 'UNESCO', 'gentrification' and 'sustainable tourism' were chosen. This combination generated only one useful result. The publication by Chan et al. (2016) [44] deals with tourist gentrification in the Honghe Hani Rice Terraces region of China using interviews and non-participant observation conducted with inhabitants. However, it is not enough to investigate the complexity of gentrification. Therefore, the search continued to investigate the remaining queries for additional results. It should be noticed that the same document was later found in subsequent searches, thus proving its relevance for this topic.

The second string used for the search contained the keywords 'UNESCO', 'gentrification', and 'tourism' and 21 documents were obtained. Out of these, 7 were not consultable, one was irrelevant to the topic and another one was written only in Spanish, so they were discarded (Fig. 1). Among the remaining papers, several case studies were considered relevant to the research goal.

To find additional academic articles relevant to the research topic, a final more general string was generated, containing only two keywords: "UNESCO" and "gentrification".

The latter produced 40 useful results, including also those found in the previous combinations. Out of these, only 17 were available for consultation. Another 5 were excluded from the analysis because the topic of tourist gentrification was only touched. For example, a paper carries out a critical review of flood management solutions for the UNESCO site of Krakow, in which it also mentions the problems of gentrification of the site. This brought the final number of consulted papers to 12, as shown in Fig. 2.

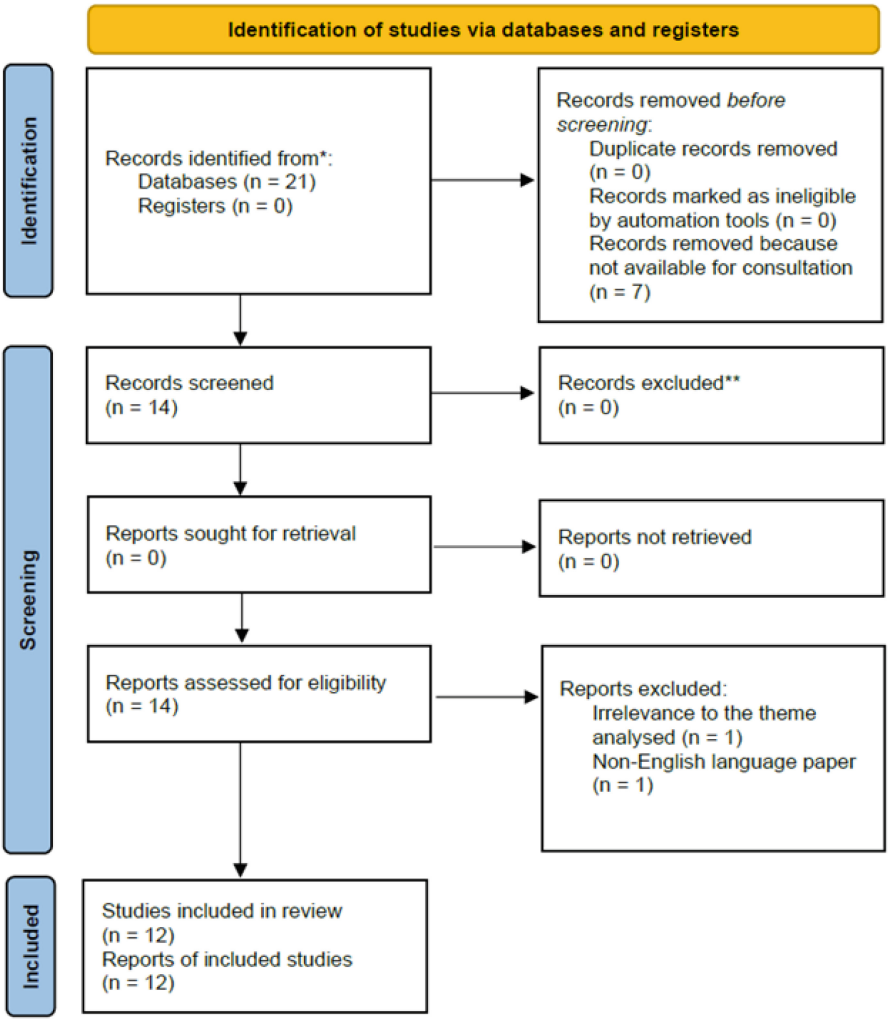

Fig. 1. PRISMA approach [14] string n.2

After this step, we conducted an initial analysis of the title and abstract to determine whether the contribution discussed the gentrification phenomenon in general or used case studies to validate the research hypothesis.

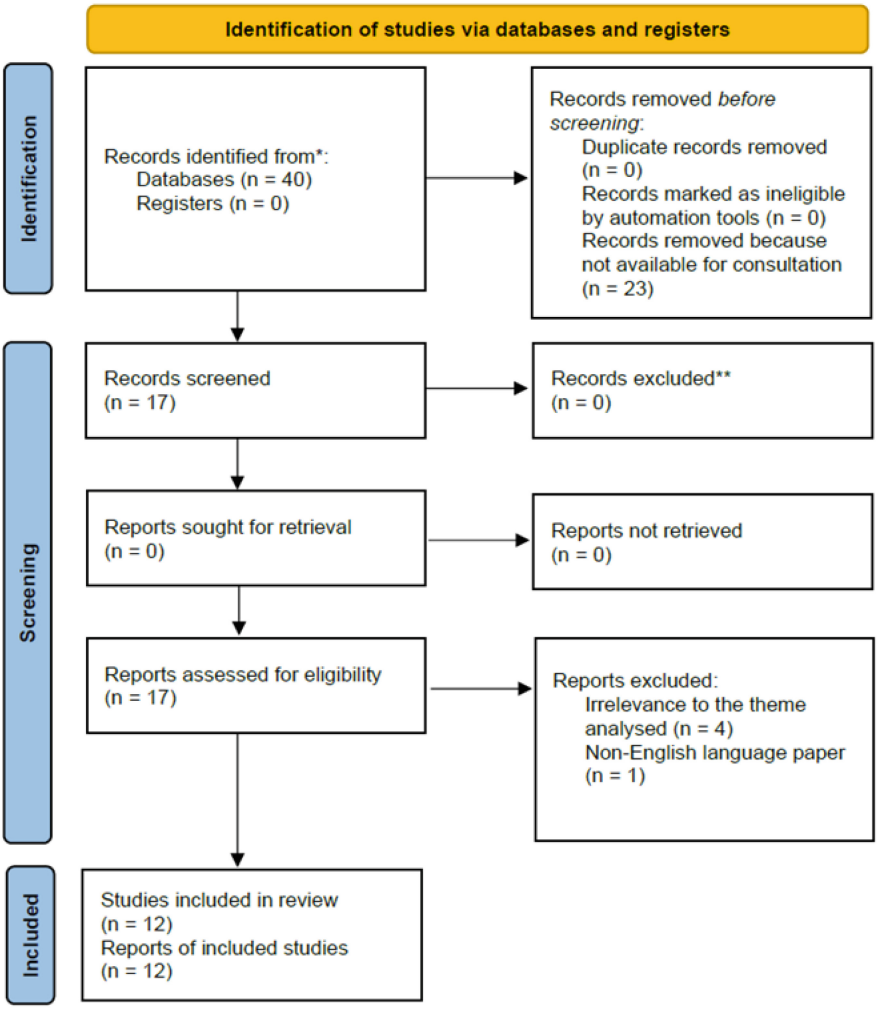

Fig. 2. PRISMA approach [14] string n.3

4 Results

4.1 Time and Location

The literature analysis was conducted from string number 3, which also includes the results of the previous two strings. It found bibliographical contributions, particularly in the fields of Social Science (34%), Arts and Humanities (15%), Business, Management and Accounting (12%), and Economics, Econometrics and Finance (10%). These contributions were published in the last twenty years, starting in 2002. However, it was not until 2010 that the literature was consolidated. As shown in Fig. 3, the number of contributions on this topic has been increasing in recent years, and case studies have been progressively used to validate hypotheses.

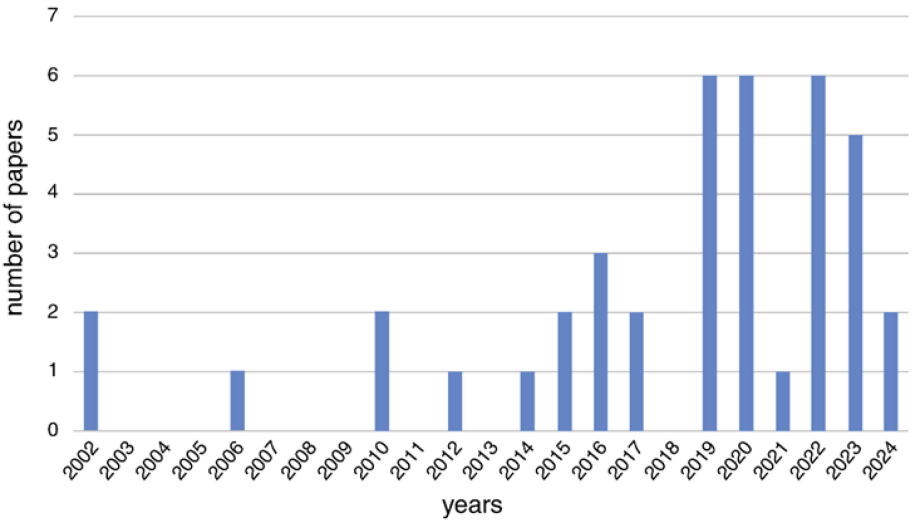

Fig. 3. Number of papers per year

The final mapping includes 13 case studies from 11 different cities worldwide and one case considering the geoparks of an entire region. The countries covered by these studies are shown in Fig. 4 and are China, Chile, Ecuador, Jordan, Laos, Malaysia, Spain, Vietnam, Yemen, and Indonesia. It is important to note that 85% of case studies are located in countries in the southern hemisphere, except for Ibiza and Cordoba in Spain. In fact, it is assumed that the inclusion of a site in the WHL can accelerate economic development and also trigger urban transformation in the South at a faster rate than in European countries [45]. Additionally, Southern countries are generally more vulnerable to gentrification phenomena, such as rapid population growth, exponential

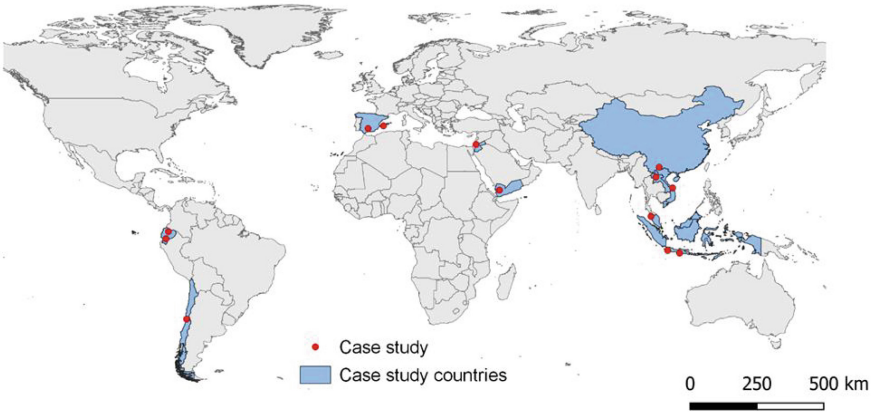

Fig. 4. Location of paper's case studies

economic development and lack of housing alternatives. These aspects explain why most scholars study this phenomenon in Southern cities rather than those in the Northern countries.

4.2 Analysis of the Papers

As anticipated in the previous section, the literature search resulted in a total of 17 papers, of which only 12 were consistent with the topic of analysis. Among these, Radaelli (2019) [46] and Hayes (2020) [47] did not use a real methodology but relied on a description of the gentrification phenomenon. In the first case, the proposal of a new governance model for the city of Cordoba is described. In the second case, the preservation of the universal heritage and urban regeneration of Cuenca, from a historical and social point of view, is highlighted. Instead, Soccali and Cinà [45] compared three WHL sites, identifying recurring patterns in each case analysed: Quito (Ecuador, inscribed in 1978), Sana'a (Yemen, 1986), and Luang Prabang (Lao People's Democratic Republic, 1995). The analysis highlighted how national neo-liberal agendas on tourism development treat urban heritage resources as commodities, hindering participatory practices. On the other hand, 'rights-based' approaches are more likely to promote awareness of local heritage values and encourage identity construction.

Other analyses in the literature primarily use sources from interviews and focus groups to analyse different case studies. This is the case of Foo and Krishnapillai (2019) [48], which investigated the enrolment phenomenon in George Town, Malaysia. They conducted interviews with various stakeholders (including local businessmen, displaced residents, old quarter residents, international and domestic tourists, tourism representatives from public and private sectors, representatives from the site management agency, local urban regeneration agency, heritage activists, and academics) and two focus groups of 8–10 people each with the residents living in the old quarter. These interviews highlighted how WHL registration generated an unprecedented capital appreciation, a surge in rents and an increase in transactions of pre-war commercial houses, inevitably triggering gentrification phenomena. Chan et al. (2016) [44] also employed interviews to collect data on the gentrification phenomenon, which was divided into three types. The researchers conducted a total of 65 interviews on the Honghe Hani rice terraces in Yemen. Of these, 25 were semi-structured interviews with pre-set questions, and 40 were unstructured in-depth interviews without pre-set questions. Ristiawan et al. (2024) [49] conducted 32 interviews with different actors in the Gunungsewu and Ciletuh UNESCO Geoparks, showing how finance and local-regional governance power are intertwined in the production of tourist destinations against state power. The last paper of this typology is proposed by Cáceres-Seguel (2023) [50], who analysed the case of the Valparaíso tourist area using 40 semi-structured interviews with residents of Concepción and Alegre hills. Residents have identified the issue of the transformation of houses into shops and hotels. This study highlights the propensity of historic Latin American cities to be more affected by gentrification.

In addition to these types of analysis and data collection methodologies, some studies integrate and support interviews with numerical data to explain certain phenomena. For instance, Woo and Khoo (2023) [51] studied the affordability of housing in the George Town World Heritage Site (WHS). After conducting a content analysis of the

literature on this subject, they proceeded with cross-sectional surveys. They structured 320 questionnaires, with one section dedicated to house prices and the other to socio-demographic information. The respondents indicated that renting after WHL registration has become too expensive, and none of the respondents were aware of any government strategies to provide access to affordable housing. Instead, the paper by El Faouri and Sibley (2022) [52] aims to retrace the process that led to the candidacy of the As-Salt site in Jordan through the collection of both qualitative and quantitative data, followed by interviews. These were conducted with different members of the local community, to gather not only their perceptions of the regenerative practices that were transforming the city but also their hopes for the future. The study investigated the perception of the local community through a content analysis using the software tool NVivo 12 [53] to code the responses. The study also used a Geographic Information System (GIS) to map the transformations in the city that occurred before and after the candidacy. The study reveals that the city has implemented tourism-driven interventions that have had a transformative effect. However, these interventions have undermined the OUV which was the reason for exclusion in the first attempt to the UNESCO candidacy process. Therefore, the focus shifted from tangible to intangible values. The study also highlighted the risk of heritage-led regeneration in this region, destroying and neglecting other important values for both the site and the local community. González-Pérez and Novo-Malvárez (2022) [54] conducted qualitative-quantitative analyses using GIS. The study integrated the potential of this tool with the Spanish National Statistical Institute's database, including demographic data (e.g. number of residents, foreigners, or people born outside the island) and tourism data (e.g. number of beds in hotels, rural hotels, and tourist flats extrapolated from tourist accommodation facilities). This study aims to examine the relationship between tourism and gentrification in Ibiza, one of the most popular tourist destinations in Spain. The findings indicated a significant social and cultural transformation in the historic centres, characterized by a decline in the local population and a rise in the number of tourists.

Finally, some papers have addressed the topic using satellite images and thematic cartographies in a GIS environment. For instance, Hidalgo (2014) [55] studied the impact of the WHL candidacy of the city of Valparaíso. The analysis of satellite images enabled the identification of transformations that occurred due to both natural and anthropic causes, as well as those specifically related to the candidacy. The results indicated evidence of gentrification, which, on the one hand, maintains the value of the built city but, on the other hand, weakens the social situation. Jones, Bui and Ando (2022) [56] study the same phenomenon in the city of Hoi An, Vietnam, which has been transformed over the years by tourism development due to the candidacy. For this study, 22 interviews with stakeholders and informal talks with the local population were supplemented with socio-economic and cartographic data. The findings were combined with secondary data, which included statistics collected by government departments, local and regional master plans and policy documents. The data were entered into the GIS with MapInfo software [57] to generate visual representations of the expanded buffer zone and the population of the different neighborhoods. The results showed that the WHL nomination brought a significant increase in tourists and a rise in Gross Domestic Product. In addition to the direct benefits of WHS investments, subsidies and ticket revenues to Hoi

An's Old Town, the indirect economic benefits have facilitated a genuine architectural renovation of the core area. However, the negative impacts of WHS status involve both economic (e.g. increased property prices) and social consequences (e.g. stricter planning regulations and increased tourist congestion).

All the analysed papers deal with the topic of gentrification always referring to case studies to validate our hypothesis. Specifically, 10 papers focus on a specific case [44, 46–48, 50–52, 54–56] one refers to two case studies in the same country [49] and one proposes a comparison between three different case studies [45].

4.3 Role of Evaluation Methods in Studying the Relationship Between UNESCO Sites and Gentrification

Two distinct categories of analysis emerged from the various papers: those employing qualitative analysis and those utilizing quantitative analysis to complement the qualitative findings. Belonging to the first category, 7 papers investigated the phenomenon through methods such as interviews, cross-sectional surveys, thematic comparative analysis, content analysis, focus groups and informal talks. In the second group, statistical analysis, and satellite and cartographic analysis, supported by the GIS tool, were integrated into previous methodologies.

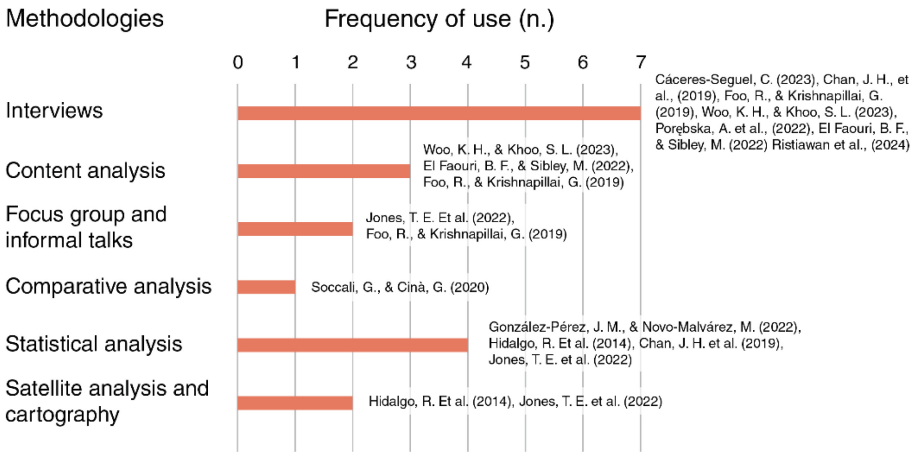

Fig. 5. Methodologies used in the analysed papers and frequency of use

Finally, in order to identify the most commonly used approaches to analysing the issue of gentrification, the study calculated the frequency of use of each identified methodology. As can be seen from Fig. 5, most of the analyses start with interviews, ranging from in-depth to simple informal conversations and focus groups. In some publications, evaluation methods are simply used to discuss qualitatively what is happening in the case studies. In other contributions, these methods are supported by quantitative data and statistical analysis to measure and monitor the phenomenon effectively. As

described in detail in the previous section, other methods found in the papers used comparative analysis, content analysis and cartographic and satellite analysis, although to a lesser extent than interviews.

5 Discussion and Conclusions

This study conducted a Scopus-based literature review to discuss the possible negative implications of tourism on UNESCO sites with particular reference to gentrification and the methodologies used to study this phenomenon. The PRISMA approach was used to present how the search results were filtered and extracted for our analysis.

The findings of this analysis led to some important reflections. It is clear that this phenomenon is well suited to be studied with qualitative methodologies that assess the satisfaction and perception of the various actors, from the local population to the decision-makers involved in territorial management. At the same time, it is also evident the lack of the use of strictly quantitative methodologies capable of extrapolating and studying the externalities produced by the phenomenon itself. From this analysis, however, it can be expected that statistical analyses will be increasingly used in these studies, thanks to the use of databases and GIS tools capable of handling large amounts of data.

In addition, a few numbers of methods have been employed to explore the phenomenon since the early stages of WHL pre-inscription. In fact, the literature review has given back many methods which are employed after the WHL inscription, such as interviews, focus group, comparative analysis, or statistical analysis among others. Thanks to the results obtained, it can be stated that an appropriate analysis could support the several stages of the process more effectively. For example, before the WHL inscription (ex-ante phase) the framing of the problem, the data gathering and statistical analysis could be supported by spatial SWOT analysis, together with statistical analysis, Stakeholder Analysis and tourism capacity calculation, since these are recognised to be very useful tools to aid decision-makers in better understanding the real scale of the phenomenon. The definition of sets of multi-spatial indicators could be suitable during the process of WHL inscription (in-itinere phase), because indicators can measure the past and current performance of the process and be also employed to simulate potential trends. Their employment could therefore aid decision-makers to intervene on negative states and trends by changing strategies. After the WHL inscription, these methods are considered very suitable to analyse and assess the phenomenon from the point of view of the various consequences. In fact, these tools are retained crucial for the UNESCO Management Plan and monitor the potential implications derived from the implementation of strategies and projects that received economic investments.

In conclusion, it is possible to state that the various methodologies found in the literature are employed to analyse and assess the phenomenon of gentrification, even if a long-term view of the capability of these different evaluation methodologies to cover every stage of the process still lacks today. In light of the goal of UNESCO to preserve, enhance and manage WHSs, and bring benefits to the surrounding area, the current and future research must be even more complete with solutions capable of minimizing gentrification, and more in general all those human and natural hazards that could affect the heritage value.

The current demand for innovative and integrated methods to support the early stages of WHL application could help on the one hand to achieve the nomination, and on the other hand, once included in the Management Plan, to predict and improve the performance of the application.

Since the present research work is ongoing, some future perspectives are identified and explained below. The first future perspective is to deepen the literature review to encompass documents that deal with the phenomenon before and after the WHL nomination (ex-ante and ex-post), noting the limited number of papers available for analysis. Starting from a limitation recognized by the authors, we do not want to focus only on the Scopus bibliographic database. Indeed, we would like to include other databases, such as Web of Science and Google Scholar, as well as national and international reports on the topic, to return an integrated and comprehensive literature review on the state of the art. In addition, a more comprehensive examination will be undertaken regarding other critical issues that characterize UNESCO sites, including commodification, alienation of local communities, and loss of authenticity, to obtain a holistic understanding of the topic. Another future perspective is to employ the founded methods in a real case study involved in an ongoing WHL candidacy process. After the potential nomination, the same methods will be directly integrated into the UNESCO Management Plan.

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Geo-NLP Insights: Unveiling Residential Real Estate Trends Through Textual Analysis

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Abstract. The physical and design aspects of buildings, the availability of urban infrastructures and services, and the presence of landscape amenities significantly influence consumer preferences for residential living spaces. Capturing these preferences can provide insights on spatial changes in consumer behavior. To address this challenge, this paper introduces a novel methodological framework that combines Natural Language Processing (NLP) with geospatial data analysis, focusing particularly on insights derived from real estate listings. This innovative approach enables an in-depth examination of urban market dynamics by allowing for a comprehensive analysis that includes temporal shifts and spatial differences. By employing advanced analytical techniques, such as lexical analysis of listings and geospatial exploration, the framework is designed to decode complex market narratives and uncover detailed consumer preferences.

The methodological framework of this paper aims to construct a comprehensive model by integrating textual, spatial, and temporal data from listings, thereby offering a complete perspective of the urban real estate market. The integration of these diverse data sources from real estate listings provides critical insights into consumer preferences and market trends, equipping stakeholders with essential information to make informed decisions. Ultimately, this approach not only broadens the understanding of the real estate market but also aids stakeholders in crafting strategic initiatives that align with the sector's evolving demands. This method facilitates informed decision-making and strategic planning in the real estate domain by leveraging the rich data found in property listings.

Keywords: Text Mining · Online housing listing · Advertising keywords

1 Introduction

Real estate is a complex field of investigation which is essential in the study of urban transformations. As it is well known, the analysis of real estate market plays an important role in the understanding of urban dynamics, highlighting the most important factors affecting housing demand and price mechanisms.

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According to the literature, there are different building's characteristics which influence market value and they can be grouped according to specific classes [1]: i) Location (or extrinsic) characteristics, which refer to the whole building in which the building unit is located; ii) Position (or intrinsic) characteristics, which consider the specific building unit; iii) Technological characteristics, which describe the typological properties of the building unit; iv) Productive characteristics, which take into account the legal and economic condition of the property.

Traditionally, real estate market analysis has been developed constructing conventional databases that display data belonging to the aforementioned characteristics, like location, surface, floor, number of bathrooms, building age, distance from parks and green areas, price and others [2].

More recently, the analysis of data has significantly improved also in the context of real estate market, thanks to the new technologies and tools belonging to data science. In this domain, a very important role is played by Machine Learning algorithms which are used to derive the estimation of a set of essential indicators [3].

In this paper, we focus on big data analytics on real estate, with specific reference to online real estate marketing; in particular, we consider advertising information to reflect on consumers preferences and how they are exhibited in the actual market trends. Indeed, real estate advertisements can offer numerous details and important information about the properties in a certain urban area. The automatic extraction of keywords from the text of the real estate advertisements can help in better understanding the area under investigation.

Our paper aims at investigating the use of the Natural Language Processing (NLP) in the real estate market analysis. Starting from text data coming from property listing portals, we applied different algorithms to clarify the possible outcomes as well as the advantages of this approach in the study of real estate.

The basic idea is that, differently from conventional databases, the use of NPL on online advertisements can capture more evidently the actual trends going on in the market and provide qualitative understanding that could be very useful for delivering a more complete picture. In this sense, the use of NPL on online listing could be more effective than transaction-based data in highlighting relevant keywords that could be employed for forecasting future trends in the market.

2 Background and State of the Art

The application of NLP in real estate offers a nuanced approach to understanding market dynamics through the lens of textual data from listings and reviews. The application of NLP in real estate provides a sophisticated means of deciphering market dynamics through the analysis of textual data found in listings and reviews.

Cadorel et al. (2023) delve into the intricacies of extracting valuable insights from the complex, domain-specific language of French real estate listings [4]. Their exploration into various text representation models reveals that bespoke, custom-tailored approaches significantly outshine generic pre-trained models in capturing the nuanced linguistic features specific to real estate ads.

Further enriching the understanding of urban real estate markets, Blanchi et al. (2022) introduce a novel methodology that marries NLP techniques with Geographic Information Systems (GIS) [5]. Their work on extracting geographic knowledge from real estate ads and identifying named entities and relationships offers a deep dive into the social and spatial structures that underpin urban spaces. This integration not only adds a spatial dimension to the analysis but also paves the way for an exploration of how location impacts market dynamics and consumer preferences, underscoring the significance of spatial analysis in comprehending the complexities of real estate market dynamics.

The study by Su et al. (2021) presents a hierarchical hedonic modeling approach based on semantic and sentimental analysis of online housing advertisements across five Chinese megacities, enriching our understanding of the dynamics between landscape amenities and the real estate market, specifically rental prices [6]. This study advances the discourse by not only affirming the value of landscape amenities in urban planning and real estate valuation but also demonstrating the variability of this value across different urban contexts. It highlights that the perceived value of landscape amenities, as reflected through online housing listings, significantly influences rental pricing strategies, thereby impacting the broader rental market dynamics.

While existing literature excels in textual and spatial analyses, the temporal dynamics of the market - especially in reaction to external events like the COVID-19 pandemic - are vividly captured in the study by Lee and Lee (2023) [7]. Their analysis demonstrates how online listings can reflect temporal shifts in consumer preferences, highlighting a growing demand for properties with enhanced views and more space, alongside a declining emphasis on proximity to transportation and business districts.

A common theme across these studies is the strategic use of NLP to derive insights from textual data, with Su et al. (2021) and Blanchi et al. (2022) providing a pivotal contribution by integrating spatial context through georeferenced data. Not least, the literature reveals the presence of the study by Lee and Lee (2023) that incorporates temporal data to provide insight into the property market over time. Despite the advancements, the literature presents a gap: the lack of an integrated model that simultaneously considers spatial, temporal, and textual data to provide a holistic view of the real estate market. Such a model could offer unprecedented insights into the dynamic interplay between market trends, consumer preferences, and external influences.

Upcoming research should aim to develop integrated models that encompass spatial, temporal, and textual dimensions to fully understand the complexities of the real estate market. Acknowledging the advancements in the application of NLP in real estate and the insights gained from spatial and temporal analyses, the overarching goal of this research is to bridge the identified gap in the literature. We propose to develop an integrated model that synergistically incorporates spatial, temporal, and textual dimensions to offer a comprehensive understanding of the real estate market. This proposed model aims to deliver a robust framework capable of unveiling the intricate relationships between market trends, consumer preferences, and external factors, providing stakeholders with a powerful tool to navigate and strategize in the complex landscape of real estate, particularly in the face of unforeseen events and market shifts.

3 Methodology

The proposed methodological framework aims to provide a detailed picture of market trends and consumer behaviors starting from real estate listings considering space and time. It incorporates spatial analysis to understand how geographic factors influence property values and buyer preferences. By temporal analysis it is possible monitoring market trends over time to understand changes in preferences and identify possible cyclical pattern.

The model is designed to be a robust framework that not only reveals the intricate relationships between market trends, consumer preferences and external factors, but also provides stakeholders with a powerful tool to navigate and strategize within the complex industry landscape real estate. This is especially important in the face of unexpected events and market changes, such as economic downturns or global pandemics, which require rapid and informed responses from market participants.

By providing stakeholders - from developers and investors to urban planners and policy makers - a comprehensive tool, this framework aims to improve decision-making processes, enabling more targeted marketing strategies, informed investment decisions and effective policy formulations. Using this model, developers can gain insights into the most desirable features and emerging trends in residential and commercial real estate. This allows developers to design and build properties that align more closely with current market demands, ensuring greater marketability and return on investment. The tool can highlight areas with rising property values and predict future hotspots, thus allowing urban planners to offer detailed insights into how different areas of a city are evolving in terms of demographic changes, housing demand and infrastructure needs. This information is crucial for planning public services, zoning and transportation networks that efficiently support urban growth and sustainability. Policymakers can use the model to understand the impact of regulations and economic policies on the real estate market. This model allows stakeholders to anticipate market changes more accurately and respond quickly. In a competitive market landscape, the ability to quickly adapt to new developments and consumer preferences provides a crucial competitive advantage, enabling stakeholders to take proactive rather than reactive measures.

The proposed methodological framework provides notable advantages over traditional real estate valuation models. While traditional models tend to rely on static comparisons and isolated numeric attributes to estimate property value, this framework integrates spatial and temporal data, starting from textual information [8, 9]. By utilizing advanced analytics such as NLP and network analysis, the framework provides a dynamic, predictive view of the market, enabling stakeholders to identify emerging trends and make proactive decisions. This holistic approach allows for a more comprehensive understanding of how geographic shifts, evolving consumer behaviors, and economic disruptions impact real estate values, offering a nuanced alternative to conventional models.

This section outlines the overall workflow that encompasses the stages from data collection to the development of local insights useful for making informed decisions. In the subsequent sub-sections, we will delve into the complexities of our research methodology, which is succinctly encapsulated in the flowchart in Fig. 1. This methodological diagram traces the path from the initial data collection to the nuanced analysis and visualization of the results. We begin our journey with a systematic collection of real estate

listings, endowed with textual and geospatial data. Subsequently, we have meticulously preprocessed the text to distill the data into a corpus ready for an in-depth NLP analysis. Computational techniques based on statistical ranking are employed to sort and prune the data, ensuring the refinement of the most salient terms. A review by architectural and civil engineering experts helps verify the consistency of the extracted features and ensures the accuracy of the results. The culmination of this process is a sophisticated network analysis, paired with a data visualization that brings the abstract data to life, transforming it into a vibrant illustration of interconnected terms and their geospatial significance.

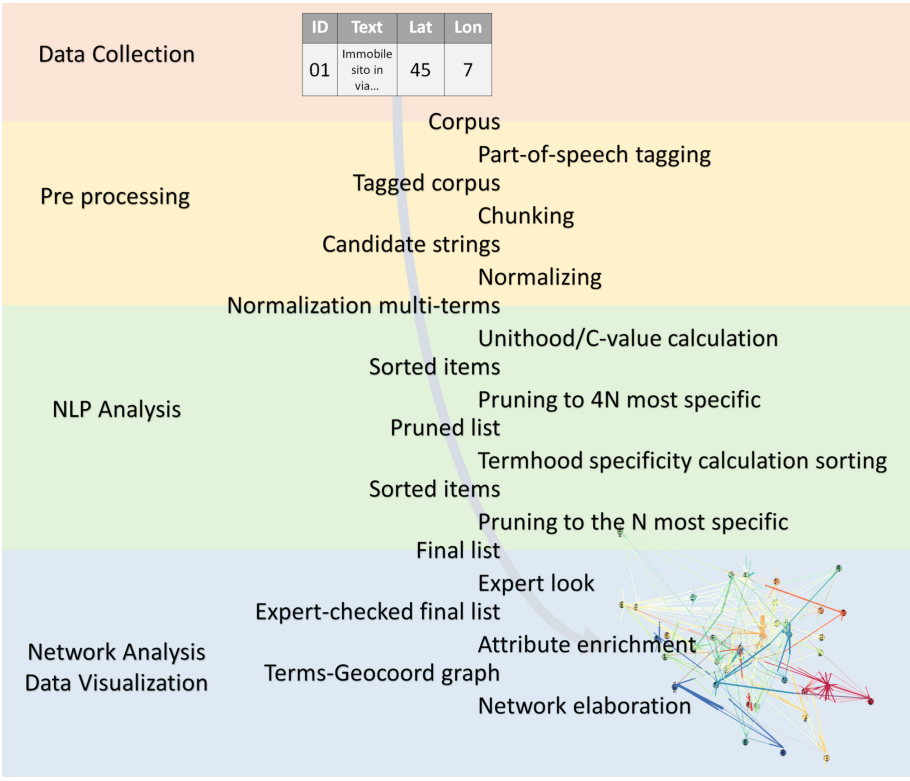

Fig. 1. Methodological workflow.

3.1 Data Collection

The framework unfolds with a data collection plan centered on acquiring a dataset enriched with detailed textual descriptions for each real estate listing, which is indispensable for the NLP segment of the study. The textual content, detailing property features, amenities, and other qualitative aspects, is essential for an NLP analysis that seeks to

capture the nuances and specific terminologies that resonate with both the inherent and the perceived market value of properties.

To conduct a nuanced analysis, it is vital to integrate these detailed textual descriptions with exact geographic data, whether that be coordinates or address-based information amenable to geolocation methods. This crucial preliminary stage ensures that the resulting dataset comprises exhaustive narrative descriptions, setting the stage for a comprehensive, text-based analytical process that will later be augmented by spatial analysis employing Geographic Information Systems (GIS) technology.

Moreover, a targeted focus on particular types of buildings is advisable, allowing for an exploration into the preferences of demographic segments that possess the financial means for certain property standards. This focused approach aims to uncover the preference trends and standards desired by specific income brackets within the population.

3.2 Data Preprocessing

Before the actual analysis both textual description and the geographic coordinates field needs a pre-processing phase. The linguistic preprocessing consists of three basic steps: part of speech tagging, chunking, and stemming.

The Part Of Speech tagging tool categorizes terms based on their grammatical category, such as noun, adjective, verb, or adverb. To process the ads we identified CorTexT Manager [15] which employs Natural Language Toolkit [10], commonly known as NLTK, for English and TreeTagger for other languages [11, 12].

During the next Chunking phase, tags are used to identify noun phrases in the corpus, that is, a sequence of nouns and adjectives. This phase creates the set of possible multi-terms. Eventually, with the normalization phase, minor spelling inconsistencies between multi-terms, including the presence or absence of hyphens, are refined, assuming, for example, that the phrases "windowed bathroom" and "windowed bathroom" belong to the same class.

The stemming phase is dedicated to manage multiple terms that can be grouped together if they have the same stem. For example, singular and plurals are automatically placed into the same class (for example, "windows" and "window" are two possible forms of the stem "window"). Porter's stemmer is used for English [13], whereas Snowball stemmers are used for French, German, and Italian [10].

Geographic coordinates are the other essential aspect to be addressed. Since the goal is to cluster the extracted terms based on geographic location, a simple and intuitive path to follow is to group ads by proximity by defining a "Microzone" attribute. In detail, a microzone, smaller in area compared to a neighborhood, represents a portion of the municipal territory that exhibits homogeneity in terms of its location, urban planning, historical-environmental aspects, socioeconomic characteristics, as well as the provision of urban services and infrastructure. These microzones therefore represent uniform areas that delineate submarkets within the real estate market. In each microzone, the real estate units are uniform in terms of typological characteristics, construction period, and predominant use. Often, real estate listing sites utilize this subdivision to facilitate users' search for properties. The microzone will be assigned a pair of latitude and longitude

values, calculated through the average or median value of ads located in the specific zone, and will be used to map the information retrieved.

3.3 NLP Analysis

Cortext function Terms Extraction automatically identifies terms pertaining to a given corpus by using Natural Language Processing tools that allow us to identify not only simple terms but also multi-terms (called n-grams). For large datasets, terms will only be extracted from sample sub-corpuses with a fixed number of documents (selected at random from the original sequential datasets). Regardless of the sampling approach used, identified phrases will be indexed throughout the whole corpus.

Frantzi et al. (2000) proposed the C-value approach to determine the unithood of multi-term stems [14]. Unithood is the degree to which a sequence of words is able to form a stable lexical unit (Wong, 2009) [15]. The frequency of terms can be calculated at the document level (i.e., the number of distinct documents in which they appear) or at the sentence level (which includes repetitions of a term across sentences within a document). The most relevant terms are chosen based on a balance of specificity and frequency. By default, specificity is calculated as a chi2 score (sum of all terms). It is also conceivable to utilize a simpler G2 score (GF-IDF for Global Frequency/Inverse Document Frequency derived from the well-known Term Frequency/Inverse Document Frequency TF-IDF). The G2 score is based on the notion that intriguing terms are likely to be repeated in the same document. One can optionally disable the role of specificity in the final ranking of extracted phrases, such that only the top N most frequent terms are retrieved (frequency). Our option has been to use the chi2 specificity, since the G2 score could "reward" repetitive ads beyond measure.

The ranking phase provide an entire list of possible multi-terms organized into stemmed classes, from which the N most relevant will be chosen. Linguists often make two assumptions when attempting to identify the most significant multi-terms in a corpus: pertinent terms occur more frequently, and longer phrases are more likely to be relevant. To sort the list of candidate phrases, a basic statistical criterion is used. To get the total number of occurrences (frequency), we count all multi-terms in the corpus that correspond to a certain stemmed class. In this phase, if two candidate multi-terms are nested, the larger chain's frequency is increased. For example, if "windowed bathroom" appears in a document, we only increment the multi-stem "window bathroom," not the smaller stem "bathroom". Items are then sorted by unithood [10], and the list is reduced to 4N multi-stems, starting with the greatest C-value [11]. This stage eliminates less frequent multi-stems, but more importantly, it enables second-order analysis of the remaining list.

Finally, Cortext use a similar method to Van Eck et al. (2011) to eliminate irrelevant multi-terms that may still be prevalent [16]. The logic is that irrelevant words should have an unbiased distribution in relation to other terms on the list, implying that neutral terms can appear in any text in the corpus independent of the precise thematic they address. We generate a co-occurrence matrix M for each item in the list. A multi-stem's termhood (θ) is calculated by adding its chi-square values to those of the other classes in the list. We rank the list depending on θ, and only the N most specific multi-stems are conserved.

3.4 Data Visualization

The extracted terms are now indexed in the original dataset, which also contains geocoded data. Specifically, each apartment in our dataset contains the longitude and latitude coordinates, which have been previously used to calculate the geographic coordinate of specific microzones. The microzone is an urban area of variable size defined in our original dataset that we use for clustering the textual information retrieved. Using the Network Mapping feature we will be able to map the extracted terms with the microzone, and export the bipartite graph that will be shaped with Gephi [17], a dedicated software for Network Analysis. The bipartite adjective refers to the heterogenous nature of the network that is composed by two different types of nodes: the Microzones (containing spatial information) and the Terms (the descriptive labels extracted with NLP).

In detail, we will use the Geo Layout plugin that will exploit the longitude and latitude coordinates to position each microzone. The position of the microzone node will then be fixed to apply a second clustering algorithm that will group terms around and in between the microzone, without losing spatial information, but actually exploiting the previously positioned nodes and the weight of the relation with each microzone to properly position the extracted Terms. Force Atlas is the force-directed algorithm used for clustering because of its readability and the peculiarity of using edge weights to position each node, which in our case is critical for identifying the most consistent position for terms that straddle two or more microzones. The final step is to resize labels based on Terms weights, with the goal of highlighting the most relevant features.

The term nodes are enriched with features that categorize them with parameters drawn from the literature, such as intrinsic or extrinsic characteristics, green infrastructures, mobility/accessibility, different facilities such as medical, educational, commercial or leisure ones, type of investment, and finally toponyms.

One aspect that requires attention in the data visualization phase are high-degree nodes that may map terms to incongruous positions due to the force-directed dynamics of the algorithm. One solution is to filter low-weight edges so as to favour terms that move close to the microzone with the highest correlation with the specific term. The label adjustment phase, the purpose of which is to increase the readability of the word map, must also be approached carefully to minimize the displacement of terms that must remain associated with the microzone.

3.5 Guidelines Definition

In the final phase of the methodological framework, a structured procedure is established to translate analysis results into actionable guidelines. This process involves synthesizing insights gained from identifying impactful keywords, mapping real estate preferences, and observing temporal variations into a coherent set of recommendations. Rather than focusing on future predictions, the framework analyses changes in the past to identify evolving market trends and shifts in consumer behaviour over time.

The utilization of these guidelines by real estate operators, urban planners, and other stakeholders is multifaceted. For real estate agents and marketers, the guidelines can offer data-driven strategies for optimizing property listings to align with buyer preferences, thereby improving engagement and potentially accelerating sales [18]. Urban

planners and policymakers can leverage these insights to inform decisions on zoning, infrastructure development, and the provision of public services, ensuring that urban interventions are closely aligned with the evolving needs and desires of the residential market [19]. Furthermore, these guidelines can serve as a valuable resource for investors and developers by highlighting emerging trends and preferences, aiding in the strategic planning of future projects. Through this approach, the guidelines aim to bridge the gap between market analysis and practical application, fostering informed decision-making that benefits a broad spectrum of stakeholders in the real estate sector.

4 Discussion

The application of this framework is anticipated to yield several key outcomes that will enhance the understanding of real estate market dynamics.

The insights derived from this procedure are expected to provide substantial benefits to various stakeholders. Real estate agents, for instance, will gain a deeper understanding of effective listing marketing strategies, enabling them to craft more appealing property descriptions. In a domain where habits and established rhetoric cover the micro-narratives of real estate marketing, the methodology used can lead to a more effective and resonant communication with respect to the specific characteristics of different markets. In fact, the data-driven approach used - able to integrate NLP and SNA for the visualisation of textual, spatial, and temporal data - can be a useful support for the definition of a "real-estate semantic of the city". The semantic could be a powerful tool not only for the elaboration of real-estate listings, but also of a more articulated real-estate marketing strategy.

For policymakers and urban planners, the findings will offer valuable guidance on targeting urban interventions and services to meet the community's housing preferences and needs, thereby enhancing the quality of urban living environments. In the context of the data-driven practice applied in fact, a further step could be taken that specifically concerns the reactions of users to the listings already included in the dataset. Each listing in fact also shows the number of online views, how many times the real-estate agency was reached by message, etc. By integrating the reaction analysis with the textual, spatial, and temporal analysis of the listings described above, it would also be possible to understand better which listings are actually most resonant for a certain audience in a selected geographical area. This further methodological step could provide significant indications for policy makers and urban planners addressing urban and social needs, as well as the real estate market priorities.

One of the primary expected results is the identification of the most impactful keywords, pinpointing property features and services frequently mentioned in listings that significantly attract buyer interest. This analysis will shed light on what aspects of properties resonate most with potential buyers, informing agents and sellers about the elements that should be highlighted in marketing efforts. Additionally, the framework aims to map real estate preferences across different geographic regions. By visualizing the spatial distribution of these preferences, it will become apparent which property characteristics are particularly valued in specific locales. This spatial analysis will reveal regional variations in market demands, offering a nuanced view of how location influences property desirability.

A further outcome includes the investigation of trends and temporal variations within the real estate market. This part of the analysis will track how preferences have evolved over time, identifying any emerging trends that could signify shifts in the residential market landscape.

As other scholars have pointed out [7], disruptive events - e.g. the COVID19 pandemic - have changed housing demands by favouring different dimensions than in the past. It would therefore be interesting to apply the described framework longitudinally by comparing the semantics of advertisements before and after COVID19 and how this has evolved in specific geographical areas. In addition to this and in a predictive way, events of a different nature but impacting on housing needs, could also be taken into account: for example, the Olympic Games and the redevelopment of entire urban areas. Understanding these temporal patterns is crucial for stakeholders aiming to anticipate market movements and adapt their strategies accordingly.

Despite the anticipated contributions of this framework, it is important to acknowledge potential limitations. These may include the availability and quality of data, the complexity of integrating and analysing diverse datasets, and the generalizability of the findings across different markets and contexts. Recognizing these limitations will be essential for accurately interpreting the results and applying the insights in practice.

5 Conclusions

5.1 Key Findings and Implications

The main outcome of this study is the development of a methodological framework capable of analysing the textual data of property advertisements with lexical, spatial, and temporal analyses. This integration would potentially allow for a detailed examination capable of capturing the complexity of real estate markets and revealing the evolution of consumer preferences and market trends over time and across geographic locations.

Using advanced lexical analysis techniques, this research could reveal important insights into consumer preferences and market trends from the analysis of property listings. It could indicate that specific attributes of properties, such as their location, technological features, and proximity to amenities, could have a significant impact on consumer decisions and property values. Furthermore, the analysis could highlight the critical role of landscape amenities in influencing consumer preferences and their effect on market prices, particularly in urban settings. This point could emphasize the importance of incorporating environmental and urban design considerations into real estate development and marketing strategies.

Furthermore, the study could illuminate how changes over time, including the effects of external events such as the COVID-19 pandemic, may influence consumer preferences and market dynamics. Information gained from the analysis of property listings over time would be essential for industry players who wish to anticipate changes in the market and adapt their strategies accordingly.

The methodology and prospective results of this research could have profound implications for future real estate market analyses. By showing the importance of combining spatial, temporal, and textual data from property advertisements, this study could pave

the way for more in-depth and accurate market analyses. Real estate professionals, policy makers and urban planners could use this information to make informed decisions, adapt marketing strategies and design urban developments that meet changing consumer demands and preferences. Through the examination of property advertisements, stakeholders could gain a clearer understanding of what determines the value of the property market and how to effectively communicate the attractiveness of properties to potential buyers or renters.

5.2 Future Possible Implementation of the Proposed Framework

The methodological framework outlined could be validated thanks to his application on specific geographic and/or urban areas. The collection of real-estate listings in the urban area of Turin (Italy) for example, could represent a significant dataset to be analyzed through the NLP approach described in the above sections. The city of Turin presents many interesting features: it has a densely populated historical center with high value properties, as long as multiple neighborhoods close to university campuses located in different areas of the city. Those areas may be also important fields to observe the transformations of the real estate marketing strategies facing a demand driven by students' housing needs. Turin also presents different amenities such as an extensive river area running through the city, multiple parks and gardens, a significant proximity to the Alps which impacts deeply on the city landscape and may also affect the demand of a real estate property with a scenic view. Moreover Turin, as a medium-size urban agglomerate in Northwest Italy, and in consideration of all the other features, could provide an interesting test-site for further applications of the methodology in different urban areas with similar characteristics at national or European level. Those analyzed features, also considered in a comparative perspective involving different urban areas, could highlight the critical role of landscape amenities in influencing consumer preferences and their effect on market prices, particularly in urban settings. That could emphasize the importance of incorporating environmental and urban design considerations into real estate development and marketing strategies. Turin area could finally represent an ideal location to validate the space dimension of the methodological approach proposed in the paper.

In relation to the real estate changes over time, the methodological approach could be validated thanks to the textual analysis of Turin's property listings in two different periods of time: in a pre-COVID19 phase (2018) and in a post-COVID19 time frame (2023). Through a longitudinal and comparative approach based on the pandemic disruptive event, many changes in the real estate marketing could be observed. As hypotheses, we may anticipate for example, an increased offer of properties located close to amenities such as the river area, or parks and gardens, or an enhanced offer of properties provided with balconies and easily accessible courtyards. Moreover, we may also notice a change in the real estate listings referred the University campuses areas: maybe we could observe an overall increase of those properties sales in consideration of the difficulties encountered by the owners during the pandemic, and the prolonged absence of the students attending classes online.

Future directions for this study could involve refining the integration of NLP with spatial statistics by focusing on detailed real estate listings for a clearer understanding of market trends [20]. Enhancing geographic tagging of property descriptions and features

could help identify emerging consumer preferences, spatial patterns in property demand, and neighborhood development trends. More sophisticated machine learning models for predictive analytics could yield accurate forecasts of market hotspots and shifts in property values. This comprehensive approach will empower stakeholders to make data-driven decisions in urban planning, investment strategy, and real estate development.

Disclosure of Interests. The authors declare that they have no competing interests.

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Innovating Urban Systems Through Nature-Based Solution for a Circular Economy Enhancement: A General Framework

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Abstract. Cities and communities are worldwide facing several issues and challenges related to global issues concerning climate change, as well as local conditions. Urban systems are the core and the key elements to pursue the transition to a more sustainable, resilient, and circular development. For this purpose, Nature-Based Solutions (NBS) are currently encouraged as technologies and strategies to support cities and communities in their transition towards sustainable and resilient development. Moreover, NBS have been recently coupled with the objective and challenges of implementing the Circular Economy (CE) paradigm in urban systems. Therefore, this article explores the relationship between NBS and CE paradigm implementation in urban systems, to highlight if this topic is discussed in literature, as well as if the evaluation of NBS with CE perspective is explored. For this purpose, this study analyses the main NBS catalogues and frameworks. The performed analysis recognizes some lacks and criticalities according to these aspects. Therefore, this research proposes a framework to collect NBS according to the scale of implementations and to provide suitable evaluation tools to assess the generated multidimensional impacts with a CE perspective. The operating principle of this framework is illustrated with a focus on urban agriculture, which has been selected according to its emblematic role in implementing the CE paradigm in urban systems. Moreover, the potentiality of the proposed framework has been discussed, highlighting the possible practical implications for practitioners and Decision Makers (DMs).

Keywords: Nature-Based Solution (NBS) · Circular Economy · Urban agriculture

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1 Introduction

Worldwide, cities, territories and societies face a wide range of multidimensional challenges related to climate change, natural disasters, and specific local conditions. These stresses and pressures ranging from population growth, economic crisis, environmental stresses, the availability of energy resources and the accessibility to affordable and safe food [1]. Moreover, current conditions will be made more and more extreme by the projected growth of urbanization, with the increase of the urban population by 68% by 2050 [2].

Furthermore, cities are at the same time the major cause of climate change in terms of urbanization, resource consumption and pollutant production, as well as the centers through which to intervene for moving towards the urgent transition to a sustainable, circular, and resilient approach of the management of natural resources such as water, food, and energy [3]. To pursue the goal of a transition to a sustainable, circular, and resource-resilient approach, many concepts and actions have been introduced, from the paradigm of "sustainable development" [4] to the concept of "urban resilience" [5], from the introduction of the Sustainable Development Goals (SDGs) [6], to the implementation of the Circular Economy model [7–10].

Sustainable development has been defined by the Brundtland Report (1987) [4] which declares that "*the sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*"

The concept of urban resilience has many definitions, however, it can be described as "*the ability of an urban system and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales to maintain or rapidly return to desired functions in the face of a disturbance, to adapt, to change and to quickly transform systems that limit current or future adaptive*"[1] [11].

The concept of Circular Economy (CE) can be addressed as an evolving "umbrella" concept which encompasses several definitions [8, 12]. However, it is possible to state that the CE paradigm aims to pursue an economic growth model which limits the consumption of new resources and reduces environmental impact (to see the used definition of CE for this dissertation, please see Sect. 2). Therefore, implementing the CE paradigm presupposes and imposes an urgent change of the modality through which human society interconnects with nature [13].

On the other hand, the Nature Based Solutions (NBS) can be described as "*nature-inspired and nature-supported, cost-effective solutions that provide simultaneous environmental, social, and economic benefits and help build resilience. Such solutions bring more nature, natural and diverse features and processes to cities, landscapes and seascapes, locally adapted and resource-efficient*" [14, 15].

Based on their characteristics, NBS have been therefore coupled with the CE concept as suitable strategies and technologies for implementing and achieving this paradigm in cities [12, 13, 16, 17]. According to this scenario, this article explores the relationship between NBS and CE in urban systems, focusing on the NBS assessment topic.

[1] Meerow et al., 2016, p. 39.

Therefore, the research questions addressed by this research can be summarized as follows:

1. $\boldsymbol{Q_1}$ "Is the relationship between NBS and CE clearly described and discussed in the literature?"
2. $\boldsymbol{Q_2}$ "How the evaluation of NBS within the CE perspective has been addressed? Are there some frameworks which proposes suitable evaluation methods or provide guidelines for this evaluation demand?".

To answer to these research questions, a methodological framework structured into two phases have been followed. Firstly, a literature review has been performed to describe the concept of CE and identify the definition to use in this research, according to the linkage with NBS (Sect. 2), as well as a focus the topic of CE in urban context (Sect. 2.1) and defining NBS and to highlight the aspects in common with CE (Sect. 3). Secondly, this research analyses the existing NBS catalogues and frameworks to address the declared research questions (Sect. 4). Therefore, according to the recognized lacks, this article proposes a methodological framework to identify NBS for CE implementation in urban systems within the indication of the suggested evaluation models to give guidelines to researchers and practitioners to overcome the current issues (Sect. 5). In conclusion (Sect. 6), this paper discusses the suitability of the proposed framework within its operative implications, as well as underlines the preliminary stage of the research describing the following development.

2 The Concept of Circular Economy (CE)

This section generally describes the peculiarities of the concept of CE, highlighting the key features related to the topic of the dissertation. It is not intended to deal with the concept of CE in its entirety and its complex literature review.

The concept of CE can be considered as an evolving umbrella concept encompassing several definitions [8, 12] to pursue an economic growth model that limits the consumption of new resources and reduces environmental impact.

However, despite the complexity and multiplicity of definitions, it is possible to identify the three founding principles of the circular economy paradigm, as defined by the Ellen MacArthur Foundation [18]:

1. regenerating natural capital;
2. keeping resources in use;
3. eliminate waste externalities.

Furthermore, based on the analysis of various definitions provided by the literature [8], it is possible to clarify the operational objective of the CE paradigm. In particular, this research leans on the definition proposed by Langergraber and colleagues [16] to address the CE challenges and principles, "*the circular economy involves the implementation of an economic system aimed at minimizing waste and making the best use of resources. In a circular system, resource inputs and losses of waste, emissions and energy are minimized by slowing down, closing, and tightening energy and material loops*".

Therefore, as above underlined the implementation of the CE paradigm presupposes and imposes a shift of the approach through which human society interconnects with

nature. Furthermore, the literature identifies different levels through which CE can be implemented to prevent resource depletion and facilitate sustainable development, or rather [19]:

1. micro-level (businesses and consumers);
2. meso-level (symbiotically integrated economic agents);
3. macro-level (cities, regions, and governments).

Therefore, it can be addressed that achieving this circular model requires cyclical and regenerative environmental innovations in the way society produces and consumes [7, 16, 20, 21].

2.1 The Paradigm of Circular Economy in Urban Systems

As mentioned in the previous section, this research mainly focuses on the implementation of CE in urban systems, therefore it addresses the macro-level of implementation within the city scale.

Defined the main principles and described what it is intended here for the CE paradigm, it is here necessary to describe what the concept of circular city means [22–24]. Also in this case, this section is not intended to deal with the concept of circular city in its entirety and its complex literature review. It aims at providing the mail pillars of this concept, to support this dissertation.

It can be generally addressed that CE is viewed as a mechanism that helps cities shift from linear to circular resource management [13, 23]. Therefore, it can be addressed that the circular city model recognizes the importance of organizing the city's systems in an analogy to the organization of natural systems [13, 23].

Furthermore, by the literature is possible to identify the main challenges of implementing the circular economy paradigm in urban systems [23, 25], these can be grouped into two main categories:

1. Preserving natural resources by reducing their import;
2. Minimizing waste production by using resources in cycle.

3 Nature-Based Solution for Circular Cities

To better understand the relationship between NBS and the CE paradigm, it is necessary to describe what it is intended for NBS. As briefly reported in Sect. 1, NBS can be defined as solutions inspired by nature with the capacity to contemporary address social, economic, and environmental challenges of cities [26]. Therefore, NBS are encouraged as technologies and strategies to support cities and communities in their transition towards sustainable and resilient development [26–29].

Furthermore, NBS are aligned with other multidimensional concepts closely related to the CE concept, such as the ecosystem approach, which promotes the integrated management of natural resources such as soil, water and biodiversity, as well as their conservation and sustainable use [16, 30, 31]. As well as, the implementation of NBS aims at maximizing the interaction between nature, society and the economy [27, 31, 32].

Therefore, NBS emerge as important implementation strategies and technologies for achieving and operationalizing the principles and challenges of the CE paradigm [13], supporting the management of resources in a circular perspective.

Furthermore, to emphasize and legitimize this statement, it is possible to cite a challenge reported by the European project ThinkNature, or rather: "*One of the most important aspects of NBSs is to consider them in a circular economy and urban innovation systems. That is, not to simply privilege them, but to see them in the light of an integrated urban development*" [17].

According to the literature [13, 25], it is also possible to state which urban circularity challenge can be addressed through NBS implementation in urban systems:

- Restore and maintain the water cycle;
- Water and waste treatment, recovery and reuse;
- Nutrient recovery and reuse;
- Material recovery and reuse;
- Food and biomass production;
- Energy efficiency and recovery;
- Building system recovery.

To better underline the increasing interest in implementing NBS in urban systems to implement the CE paradigm, some European projects and initiatives are here listed. The main projects are:

1. "COST ACTION - Implementing Nature-Based Solutions (NBS) for creating a resourceful circular city"[2]. This action aims to test that the hypothesis of implementing NBS to efficiently manage nutrients and resources in the urban context should head to a sustainable, resilient, and healthy urban environment. According to this objective of closing the resources cycle within urban metabolism, the project focuses on five dimensions: (1) built environment, (2) urban water, (3) resource recovery, (4) urban farming, and (5) socio-economic impact.
2. "CAP NET – Water knowledge for all"[3]. This project proposes an online course entitled "NBS for creating circular cities"[4]. This class aims to provide the required knowledge about creating a circular city by implementing NBS. It gives pillars about resource flows and management in cities, selecting the appropriate NBS for managing resources, and it provides some implementation examples to help understand this complex domain.

These examples demonstrate the increasing interest and efforts in implementing NBS to achieve the CE paradigm at the urban level. Therefore, it can be addressed that by incorporating NBS, cities can create regenerative green urban spaces, sustainable buildings, and prospering communities, while minimizing resource imports and waste production [13, 25].

[2] https://www.cost.eu/actions/CA17133/ (last seen on May 7, 2024).
[3] https://cap-net.org/ (last seen on May 7, 2024).
[4] https://cap-net.org/circularcities/ (last seen on May 7, 2024).

4 Analysis of NBS Existing Catalogues and Frameworks

As underlined before, to answer to the above-mentioned research questions Q_1 and Q_2, the existing NBS framework and catalogues have been analyses to underline both strengths and weaknesses concerning the research demands.

In literature, several catalogues and frameworks have been provided by many European projects. The study proposed by Stessens and colleagues (2022) [33], proposes a complete overview of the main NBS catalogues developed within different European projects.

In this context, the main listed catalogues have been analyzed and compared which are [33]:

- UNaLab: NBS technical handbook [34];
- ThinkNature – Nature Based Solution Handbook (THK) [35];
- Urban GreenUP – NBS Catalogue [36];
- CLEVER CITIES Catalogue NBS [37];
- Klimatek project [38].
- Nature4Cities [39];
- Naturvation [40];
- URBiNAT [41].

Table 1 analyses and compares the selected catalogues according to these criteria:

1. Presence in the catalog of NBS definition;
2. Reference and dissertation about the linkage between NBS and CE paradigm and challenges in urban systems;
3. Guidelines to assess multidimensional impacts generated by NBS implementation.

According to the developed analysis (Table 1), it is possible to address that the information provided by NBS catalogues cannot be considered homogeneous. Firstly, the description of what is intended for NBS is not provided in every catalogue. It is clearly discussed only in four of the considered catalogues, or rather (1) UrbanGreen UP, (2) Klimatek project, (3) nature4Cities, and (4) Urbinat. Secondly, it is possible to state that most of the analyzed catalogues do not address the linkage between NBS and the CE paradigm and challenges in urban systems, despite the great attention to the topic as highlighted in Sect. 3 and by the performed literature review [42–47]. The catalogue provided by ThinkingNature is the only one that stresses this topic, underlining the importance of NBS as a strategy to implement CE paradigm in urban systems (please see the citation in Sect. 3). Thirdly, it can be addressed that information about NBS multidimensional impact assessment are not homogeneously and comprehensively given. More in detail, it is possible to underline that a few times economic impacts are not addressed and described at all, as in the cases of UnLab and Klimatek project. As well as, it can be pointed out that in most cases the multidimensional impacts are mainly qualitative assessed, without providing information about the applied evaluation methods.

However, in this context, it is necessary to highlight that Naturvation project analyses in-depth the topic of NBS multidimensional impacts assessment according to social, economic, cultural, and environmental dimensions [40]. Furthermore, it proposes methods to assess these impact though monetary terms, to give a comprehensive evaluation

Table 1. Analysis of the considered NBS catalogues and framework

Catalogue	NBS definition	Reference to NBS and CE	Information of impacts assessment			Ref.
			SOC.	ECO.	ENV.	
UNaLab	✗	✗	✓*	✗*	✓*	[35]
Think Nature (THK)	✗	✓	✓*	✓*	✓*	[36]
Urban GreenUP	✓	✗	✓*	✓*	✓*	[37]
Clever cities	✗	✗	✓*	✓*	✓*	[38]
Klimatek project	✓	✗	✗	✗	✓	[39]
Nature4Cities	✓	✗	✓*	✓*	✓	[40]
Naturvation	✗	✗	✓	✓	✓	[41]
Urbinat	✓	✗	✓*	✓*	✓*	[42]

Legend	
✓	present in the catalogue
✗	not present in the catalogue
SOC	social impacts
ECO	economic impacts
ENV	environmental impacts
*	the impacts are evaluated qualitative

[40]. However, Naturvation project does not provide evaluation method to assess NBS within CE perspective. On the other hand, the Nature4cities project proposes the Lyfe Cycle Assessment (LCA) and provides multidimensional indicators [39]. These methods could also be useful in the perspective of NBS assessment with a CE perspective.

According to the performed analysis, it is possible to state that no comprehensive and homogeneous description and classification of NBS are provided. As well as, the assessment of NBS multidimensional impacts in not in-depth discussed, within a main lack in addressing NBS within CE perspective. Therefore, it can be addressed that a framework that provides the basic background of NBS interventions and guidelines for the selection of evaluation tools suitable for the assessment of the multidimensional impacts generated by NBS with the perspective of the implementation of CE paradigm in urban systems is required.

5 The Proposed Framework

According to the above-mentioned lacks and the objective of this research, this section proposes and describes the general structure of a new collection framework of NBS intervention typologies. Furthermore, it is necessary to underline that the proposed framework is not presumed to be an overall and final framework, it aims at proposing the useful general structure to be further implemented.

The proposed framework aims to give information related to:

1. Scale of implementation. This information is considered fundamental to propose a categorization of NBS according to their scale of implementation. More in detail, three different scales of interventions have been identified (1) building scale, (2) neighborhood scale, and (3) municipal scale. This classification has been selected to identify to which scale different NBS interventions are referred and also to support the designing process;
2. NBS intervention typology. According to the scale of implementation, this framework can list different types of intervention. In detail, this section will be implemented by the collection of the provided information of existing NBS catalogues that need to be homogenized [34–41].
3. Evaluation methods. This section should provide information on the evaluation models that can be used to assess NBS with CE perspective, which is the point most highlighted as lacking in the previous analysis.
4. Source. This section lists the references of the main case studies in which the proposed evaluation methods are applied to give information and guidelines to apply them in other contexts.

Table 2 illustrates the general structure of the proposed framework with some examples of NBS interventions classified according to the scale of implementation.

Table 2. General structure of the proposed framework

Scale of implementation	NBS interventions	Evaluation methods	Sources
Building scale	Examples: green facades, green roofs		
Neighborhood scale	Examples: urban orchards, Regreening spaces between buildings		
Municipality scale	Examples: urban agriculture		

Table 3 illustrates one example to illustrate how the proposed framework works and how it can support the evaluation of NBS according to multidimensional impacts with the CE perspective. More in detail, urban agriculture has been selected to represent the functioning of the proposed framework according to its emblematic role in implementing the CE paradigm in urban systems, according to its capability to address several CE challenges, as underlined in Sect. 3 by describing the COST Action project [16, 48, 49].

Table 3 describes the NBS related to urban agriculture according to the scale of implementation that is the municipal scale, according to the fact that it can be implemented within different approaches according to the available space from traditional systems to vertical farming, to small decentralized systems such as shared neighborhood gardens [16, 44]. Moreover, the framework reports and proposes different evaluation methods to address and assess this NBS according to the CE paradigm in urban context. Moreover, the main references of the application of the proposed evaluation methods are reported to give suitable information about how to reply these evaluation.

Table 3. Scheduling of urban agriculture NBS according to the proposed framework

Scale of implementation	NBS intervention	Evaluation methods	Sources
Municipality scale	Urban agriculture	Life Cycle Assessment (LCA) Life Cycle Cost Analysis (LCC)	[50, 51]
		Multi-Criteria Analysis (MCA)	[52]
		Indicators-based model for stakeholders' perspective evaluation	[53]

According to this brief and practical example, it can be addressed the suitability and capability of the proposed framework to provide useful and operative information about the typology of NBS, their scale of implementation and how it is possible to assess them according to the CE perspective. This information can support in operative way researchers, practitioners, planners, and Decision Makers (DMs).

6 Conclusion

According to the increasing attention to NBS implementation strategy in urban systems [26], the present paper explores the relationship between NBS and CE paradigm implementation in urban systems [42–47], in order to address two research questions $\boldsymbol{Q_1}$ and $\boldsymbol{Q_2}$ (Sect. 1). For this purpose, this research developed a general literature review about the main considered concepts and it explores the main NBS catalogues developed within several European projects to analyze the provided information and guidelines [33].

From the performed analysis (Sect. 4) it has been possible some criticalities. First of all, catalogues and framework are not providing aligned and homogeneous information. As well as, many times the topic of NBS evaluation in briefly discusses and operative suggestion are not provided. Moreover, on the catalogue by ThinkNature [35] addresses the linkage between NBS and CE paradigm and challenges in urban systems, despite the great interest of this topic in the literature [13, 25, 43–47].

According to this state of the art, this research proposes the general structure of a new framework to recognize and collect NBS according to (1) scales of implementation,

(2) intervention NBS typologies, (3) evaluation methods within CE perspective, and (4) reference of developed case studies. The main objective of this framework is to collect in a unique framework the information provided by the existing catalogues [34–41]. More in detail, this essay illustrates the functioning of the proposed framework with the illustration of urban agriculture NBS, according to its emblematic linkage with CE paradigm implementation [16, 48, 49]. Moreover, by this example is possible to underline the operative implication that this framework should have in implementing NBS for CE achieving in urban systems. It can support planners, researchers, practitioners, and DMs in briefly categorising NBS according to their scale of implementations, as well as giving useful information and examples about how to assess them within CE perspective, to address this achievement.

However, it has to be underlined that this proposed framework is not to be presumed as comprehensively developed. It has to be considered as a starting point to collect information through homogeneity and a general overview of available evaluation methods to assess generated multidimensional impacts within CE perspective.

Therefore, the future development of the proposed research foresees the implementation of the proposed framework by collecting and describing other NBS to map all the considered scales of implementations to construct an operative tool that provides the basic and common knowledge to encourage interdisciplinary collaboration [54] between planners, architects, DMs, and local stakeholders for NBS designing for CE implementation in urban systems.

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Evaluation of Land Use and Environmental Comfort in Reinventing Cities Competition: The Case of La Folie, Bobigny, France

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Abstract. The growing anthropogenic pressure on cities in recent years requires the adoption of a holistic approach to address the climatic adversities resulting from human activities. Taking into account the multifaceted impacts of urban expansion, spanning social, physical, ecological, and technological dimensions, this study focuses on devising a hybrid methodology to assess these implications consistently.

Using the Reinventing Cities area "La Folie" in Bobigny, France, as a case study, this methodology aims to regenerate abandoned urban spaces into vibrant community hubs while mitigating negative burdens such as gentrification, social segregation, and environmental degradation. By combining the Analytic Hierarchy Process (AHP) model and SWOT + STEEP analysis with Stakeholder Analysis and Scenario Building, this approach facilitates comprehensive examination of various factors, addressing the complexities of global issues. Through the evaluation of economic, social, comfort, and environmental implications based on built surface area and soil use percentages, the model seeks to advocate for alternative methodologies that promote sustainable development. By clarifying stakeholders' perspectives, decision-makers are equipped with a robust framework to navigate conflicting goals and make informed decisions, fostering the dissemination of innovative techniques conducive to sustainable development paradigms. Eventually, the findings indicate that 60% of built area is the suggested ratio for a well-designed infill development that takes into account all the implications above, as well as soil sealing effects.

Keywords: Analytic Hierarchy Process (AHP) · infill development · soil sealing · multidisciplinary decision making · land use

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1 Introduction

Rapid urban expansion is a process occurring across many regions of the world. Since 2008, the global populations have shifted from mostly rural to urban, [1, 2] and this trend is expected to continue, with the latter projected to reach 6.3 billion by 2050 [3]. This rapid urbanization across the globe poses significant challenges, including environmental, socio-economic, and spatial ones.

The driving forces behind this phenomenon primarily stem from the beneficial impact cities have on economic growth and technological innovation [3].

In the past years, the fast pace of urbanization led to a high need of new zones for residential spaces, public facilities, commercial ventures, and other urban land uses. Nonetheless, the lack of clear urban limits has resulted in the emergence of urban sprawl, which in turn led to an increase in various issues such as commuting distances and consequent traffic volume, air pollution, anthropogenic impact, and loss of open land. The expansion of a city's perimeter is unavoidable up to a certain point in its development, however, the continuous increase of urban limits cannot persist indefinitely, as reached a certain threshold it becomes a catalyst for the challenges described above [4].

In recent years, greater focus has been placed on sustainable urban development and the concept of smart growth, which comprises different urban expansion principles opposed to urban sprawl, such as mixed land use, infill development, pedestrian-scaled design, transit-oriented design, and preservation of open space [5, 6].

Urban densification is being supported in many European countries as a strategy to reduce air pollution, automobile dependency and the consumption of land [7]. Even though increasing density is a crucial component for contributing to sustainable development, it is insufficient for tackling the critical challenges of our time. For compact growth initiatives to be successful, for example, it is crucial to examine how they will impact local amenities and the way in which residents perceive these effects [8].

In this paper we investigate the possible advantages of a de-sealing strategy through a multi-level methodology analysis. For doing that, we examine which is the optimal land cover percentage for promoting the infiltration process of rainwater into the ground by taking into account four different criteria: 1) Environmental healthiness, 2) Comfort, 3) Profitability, 4) Social fabric. As a result, a reduction in soil sealing helps mitigating urban heat island (UHI) effects, recharge groundwater aquifers, and reduce the risk of flooding, contributing to healthier, more livable urban environments.

The following chapters discuss in detail the methodology and lessons learnt from the case study. In Sect. 2 we define the methodology for developing a multi-criteria analysis, composed by a Stakeholder Analysis, a SWOT + STEEP Analysis, a Scenario Building to delineate the decision problem and a multi-level ranking technique "AHP" for evaluating and resolving the problem. Finally, Sect. 3 consists in the application of the methodology to a case study and Sect. 4 discusses the research outputs and sets some concluding remarks.

2 Integrated Multi-level Methodology

The multi-level methodology integrates various evaluation models aimed at supporting the assessment of policies, plans, and projects within urban transformations. Recognizing the complexity inherent in urban design processes, characterized by multiple stakeholders and conflicting values, the integrated assessment paradigm is proposed to combine different approaches.

The proposed methodology follows three main phases: problem framing, construction of alternative scenarios, and evaluation of the problem for the selection of the best alternative [9].

The research focuses on this methodology to address the more sustainable choice for the case study regeneration.

2.1 Framing of the Problem

During the problem-framing phase, a broad analysis of the case study is conducted alongside Stakeholder Analysis to understand the involved actors and their potential support or opposition to strategies, to make them effective [9, 10].

A Stakeholder Analysis is necessary in the field of urban development to identify and analyse the interests of organizations and individuals who have a stake in or can influence urban development projects. The complex challenges faced today, including rapid population growth, climate change, and resource limitations, necessitate addressing diverse interests among stakeholders. Thus, determining which stakeholders should be involved in urban development projects poses a dilemma for decision-makers [11]. Developing frameworks to identify and map stakeholders is necessary for addressing societal challenges comprehensively [10].

The first step for this mapping involves categorizing stakeholders according to certain attributes. This includes determining their scope of influence (whether it is national, regional, or local), categorizing their affiliation (whether they are political, bureaucratic, special interest, general interest, or experts), and assessing the resources they wield (such as political, economic, legal, or cognitive resources). Additionally, it entails understanding their roles and expectations within the context of the analysis [12].

Once mapped, obtaining a comprehensive understanding of stakeholders' concerns, and managing conflict requires practical analysis methods [11].

In this research, a combination of the Power-Interest Matrix (P/I) and the Social Network Analysis (SNA) is proposed to evaluate stakeholders.

Power/Interest Matrix. Power/Interest Matrix is an evaluation tool to categorize stakeholders based on their level of power and interest in the project. By plotting stakeholders on the power/interest matrix, project teams can prioritize their engagement strategies and tailor communication and management approaches, ensuring that key stakeholders are effectively engaged, and their concerns are addressed throughout the project lifecycle [13].

Social Network Analysis. Social Network Analysis (SNA) offers a dynamic lens through which to understand social structures. Rooted in sociology and anthropology, it emphasizes the intricate web of relationships between stakeholders within a network. By identifying and analysing these relationships, SNA provides actionable insights for improving collaboration, communication, and decision-making within the network. Through visual representation and quantitative analysis, SNA enables stakeholders to grasp the complexity of their networks and identify key influencers, connectors, and hubs. This facilitates informed decision-making and strategic planning, enhancing overall network effectiveness [11].

2.2 Alternative Scenario Construction

Strategic planning using scenarios has gained significant traction in recent decades, highlighting the need for more effective long-term policies. Since the early 1980s, efforts have been made to integrate prospective and strategic planning [14].

This integrated approach, designed to guide companies in formulating strategies based on realistic and contextually sustainable forecasts, can also be applied to urban and regional planning for the adoption of sustainable policies and plans [9, 14].

SWOT + STEEP Analysis. The SWOT analysis, originating from research conducted in the 1960s, is a strategic planning tool used to assess internal strengths (S) and weaknesses (W), as well as external opportunities (O) and threats (T) [15].

Originally emerged as a response to the shortcomings of corporate planning in managing change effectively, this methodology has evolved into a widely used strategic planning tool applied across various fields, including urban and territorial development [15, 16].

Methodologically, the SWOT analysis appears as a four-quadrant matrix that distinguishes between existing endogenous factors, which are variables within the system that can be directly modified, and possible exogenous factors, which are external variables influencing the system [9, 16].

SWOT Analysis is often paired with complementary tools to enhance and structure outcomes more effectively, such as the STEEP Analysis (STEEP + SWOT). STEEP Analysis encompasses the components of Society (S), Technology (T), Environment (E), Economy (E), and Policy (P), evaluates various facets within a given context. This comprehensive SWOT + STEEP analysis, provides insights into the intricate dynamics of critical areas and is a newer method utilized in decision-making processes to offer a clearer understanding of the influential factors shaping potential objectives and transformation scenarios [9].

Dynamic SWOT. The traditional SWOT analysis fails not relating its elements to each other. Thus, the Dynamic SWOT introduce pairwise comparisons between all identified elements, regardless of category, allowing for a more comprehensive understanding of relationships and identification of predominant factors, and enabling a more in-depth and dynamic analysis of the evaluated situation [17].

The procedure involves creating a square matrix containing all identified elements, then conducting pairwise comparisons between each row element and each column element. Then a value indicating the degree of synergy between the two compared

elements is assigned. This process provides a clearer understanding of the relationships between the elements and identifies which ones are predominant and have a greater influence on others. Overall, Dynamic SWOT provides a more effective approach to evaluative analysis [17].

Scenario Building. Scenarios serve as a valuable tool for organizations to anticipate potential future situations, fostering flexibility and innovation. They offer descriptions of future situations and events, aiding in the transition from present to future states [18].

By incorporating the interests of all stakeholders, this approach fosters political consensus [9].

In scenario planning, a finite number of scenarios for future transformations is considered, typically ranging from three to five. This approach allows decision-makers to compare different scenarios and facilitates the transition towards sustainable integrated spatial planning [9, 18].

2.3 Evaluation of the Problem

In the problem evaluation phase, the constructed scenarios are assessed to investigate the most sustainable alternative.

Decision-making involves the selection of criteria and alternatives. [19] Among the different multicriteria methods, the Analytic Hierarchy Process (AHP) is chosen.

Analytic Hierarchy Process (AHP). The Analytic Hierarchy Process (AHP), proposed by Saaty in 1980, stands as a pivotal method in multicriteria decision-making, offering a comprehensive framework for handling complex decisions by facilitating comparisons among different options. Grounded in a multi-criteria measurement theory, AHP enables the derivation of relative priority scales on absolute scales, regardless of whether the comparisons are discrete or continuous within a multilevel hierarchy structure [20, 21].

AHP encompasses both tangible and intangible elements in evaluations, integrating real data and expert subjective decisions. Following the AHP methodology, complex problems are dissected into sub-problems organized hierarchically. Each level of the hierarchy represents a set of criteria or attributes related to its respective sub-problem, with the top level denoting the overarching goal and intermediate levels signifying factors from upper levels. Alternatives or actions to achieve the goal are situated at the bottom level [20].

The AHP analysis operates on three fundamental principles [21].

1. Problem Decomposition: The decision-making problem is broken down into hierarchical levels, establishing unidirectional hierarchical relationships from the top (objective) to the bottom (alternatives).
2. Pairwise Comparison: Decision elements are compared pairwise concerning their importance for their controlling criterion. Decision-makers provide relative importance values using a 9-point scale, known as “Saaty’s Fundamental Scale”.
3. Synthesis of Preferences: After constructing comparison matrices, relative weights of elements within each level are computed using the eigenvector associated with the largest eigenvalue of their comparison matrix. Consistency is measured using Saaty’s consistency index (CI) and consistency ratio (CR), with CR values below 0.1 considered acceptable.

AHP has gained widespread acceptance in the international scientific community as a robust and flexible multi-criteria decision-making tool. It finds applications in various domains, including hydropower systems, for impact evaluation, risk analysis, financial evaluation, and assessment of alternative projects [21].

3 Application

The process described in the previous chapter was therefore applied to the case study under analysis. Figure 1 shows the methodological pipeline used.

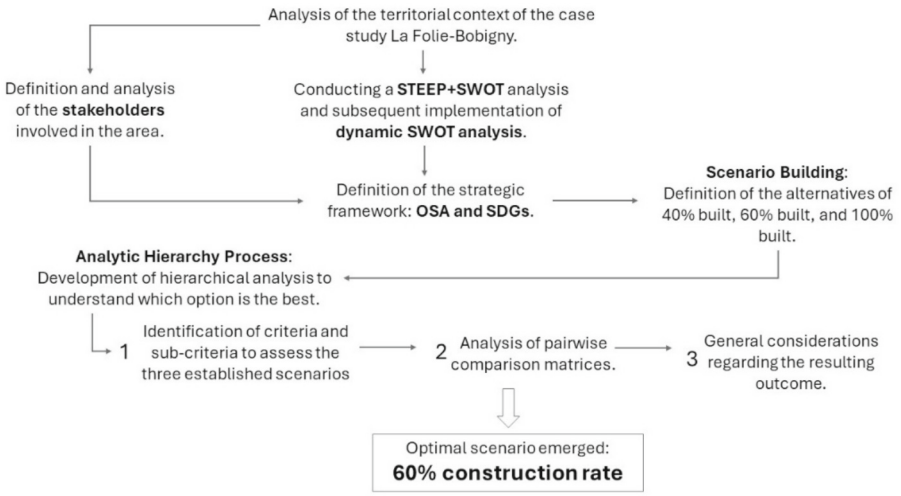

Fig. 1. Methodological pipeline synthesis.

3.1 Case Study: La Folie – Bobigny

The area under investigation is located in the southern part of the municipality of Bobigny, in the northeast outskirts of Paris. The territory is situated in the small Parisian crown, within the Île de France region, and falls within the inter-municipal structure of Est Ensemble, as shown in Fig. 2.

Specifically, the study area is part of the broader planning area of Plaine de l'Ourcq, a plain named after the canal that runs through the municipality of Bobigny. The urban context of this area, characterized by an industrial and logistical past, is currently influenced by significant infrastructures such as the Meaux road (formerly RN3), the A86/63 highway network, and the railway.

Additionally, the project area is part of a series of territorial development plans called ZAC (Zone of Concentrated Development) and, more specifically, falls within the framework of the ZAC Ecocité plan. The latter aims at the redevelopment of the banks

of the Canal de l'Ourcq and the reconstruction of the urban fabric, contributing to the overall progress of the area.

The project area was involved in the 2018 Reinventing Cities (RC2018) competition, which proposed the development of a mixed-use commercial and residential project. This entailed creating active ground floors, functions at a metropolitan scale (such as hotels, services, commercial activities, and logistics), and the construction of a pedestrian bridge over the canal. The stated objectives in the competition were as follows:

Making the Canal Visible in the Metropolitan Context of Grand Paris: Recognized as a historically significant element and a pillar of territorial identity, the project aims to enhance the canal as a unifying element, serving as a lever for significant urban transformation. The goal is to improve the green and blue landscape, creating an exemplary place that enhances panoramic views and becomes an urban landmark. The canal is envisioned to become the focal point for new metropolitan uses, including active mobility, river ports, recreational activities, and artistic and craft production.

Redesigning the Connection with the Canal and Transforming RN3 into an Urban Boulevard: The idea is to orient the city towards the canal while simultaneously maintaining existing economic activities. The project aims to create new canal crossings, particularly near the new La Folie station (M5, T11 Express, Cable Car), through the construction of footbridges or the restructuring of existing major crossing structures such as the Pont de Bondy.

Requalifying Urban Attractiveness and Giving a New Impetus to Economic Activity: The conversion of single-purpose industrial buildings and areas is seen as a key opportunity for urban and economic revitalization. Plaine de l'Ourcq aspires to become a territory that promotes a mix of urban and functional uses, also serving as a laboratory for innovation and experimentation in smart city concepts. Intensifying economic programs, with a focus on tourism, daily activities, culture, and sports, including the implementation of the concept of "rez-de-chaussée actifs" (active ground floor), will contribute to making the canal attractive through a diversification of uses.

Moreover, the objective is to determine the optimal scenario for promoting redevelopment and good design from a social, economic, and environmental perspective, with particular attention to sustainability and climate resilience, closely tied to the amount of land occupied by the new project and its consequent soil sealing effect.

The integrated method is then applied to the project area, starting with cognitive analysis, and concluding with scenario selection, we take into account how much land will be occupied by the built part and what percentage will remain undeveloped. Managing the intrinsic complexity and contradictions of the area represents the most challenging aspect of the decision-making process.

Stakeholder Analysis. Once the key stakeholders were identified (Fig. 3), they were categorized based on their level of influence and interest using the Power/Interest matrix, as shown in Fig. 4.

Based on the Social Network Analysis (SNA) model, this analysis was integrated with an examination of existing and potential relationships among the involved actors, as shown in Fig. 5.

As previously mentioned, the area in question underwent the RC2018 tender, through which the Municipality of Bobigny decided to promote the redevelopment of the Folie

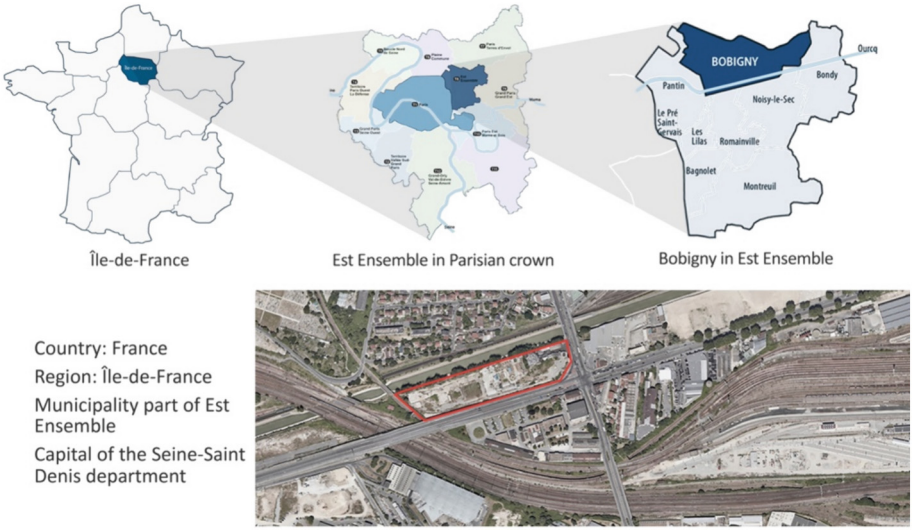

Fig. 2. Description of the area

area. The allocation of the area was entrusted to the company Sequano Amenagement, tasked with preparing it for subsequent development.

Upon completion of the design phase and the establishment of a purchase agreement for the area by the winning team, the project will be implemented through a public-private partnership. In this context, the winning team will bear all the construction and remediation costs of the area, while the Municipality will cover expenses related to the redevelopment project.

Based on this scenario, the various stages of the process were identified: Start, preliminary, executive, construction, end of work and building use. Subsequently, three methodologies of representation and analysis were employed to map the project's stakeholders.

Initially, using the matrix typology, a list of the main stakeholders was compiled to verify their presence in different phases. Subsequently, after the actors actively involved in the decision-making process were identified, they were categorized based on level (national, regional, or local) and type (political, bureaucratic, special interests, general interests, and experts). This phase of actor identification enabled careful monitoring of categories of individuals with greater potential influence on the project at all its stages.

The involvement in the decision-making process is crucial for all other actors and stakeholders, each with different degrees of engagement based on the quadrant they occupy. This is imperative to ensure maximum transparency and foster the acceptance of decisions across all involved parties. The successful implementation of this strategy is the key to minimizing and alleviating conflicts stemming from differing opinions, thereby enhancing the prospects of intervention success.



Fig. 3. Stakeholders and actors list, divided by Dente's (2014) criteria.

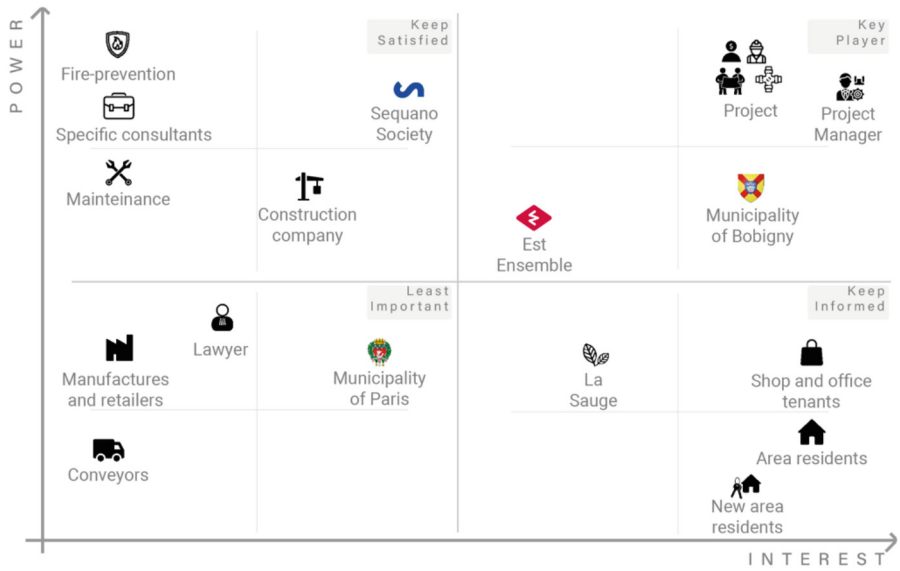

Fig. 4. Output of P/I Stakeholders Analysis.

3.2 SWOT + STEEP Analysis

The combined utilization of SWOT analysis and STEEP analysis, as we can see in Table 1, facilitated the recognition of the distinctive features of the intervention area.

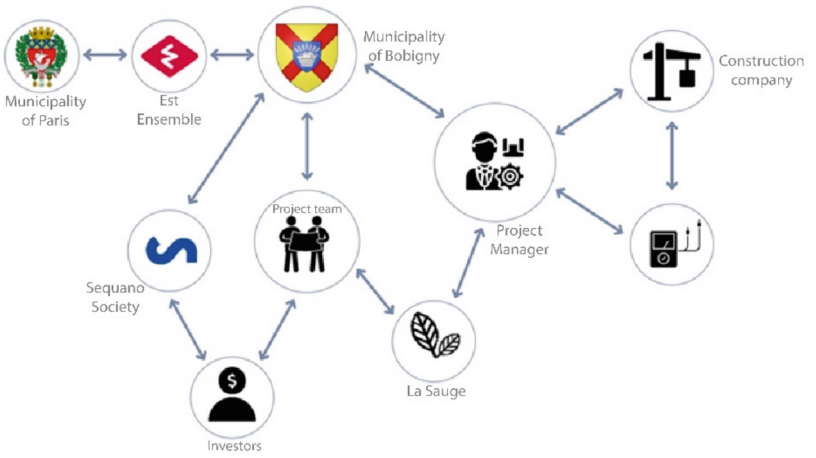

Fig. 5. Output of SNA Stakeholders Analysis.

Regarding strengths, the green areas near the project site and the presence of neighbourhood services have been positively highlighted. However, significant weaknesses have been underscored in the form of noise pollution. Concerning opportunities, potential points for expanding public transportation lines have been identified. Simultaneously, risks have been noted, including the degradation and abandonment of industrial buildings and green areas.

Understanding the territorial context and its characteristics has been crucial as support in the critical phase of developing the Dynamic SWOT Analysis. It was chosen to present a summarized representation of the dynamic SWOT analysis, encapsulating the fundamental comparison process underlying the conducted analysis (Fig. 6). Only a portion of the comparison performed was depicted, focusing specifically on the comparison between the strengths and weaknesses analysed.

Beginning with the STEEP approach, the initial step involved associating an identification code with various categories within the analysis sectors. Subsequently, the matrix of the dynamic SWOT analysis was structured, aiming to compare each row element with every column element through binary comparison, assigning a rating from +2 to -2. In this structure, influenced elements are represented in the rows, while influencing elements are in the columns.

3.3 Strategic Framework: OSA and SDGs

Through the SWOT + STEEP analysis, various perspectives of future scenarios have been outlined, focusing on the development of goals, strategies, and actions (OSA) aimed at guiding the design phase with maximum effectiveness. From the SWOT + STEEP analysis, three key factors have emerged to integrate into the design phase, with specific attention given to environmental goals, the redevelopment of connections, and the creation of an attractive hub acting as a network of attraction for the entire Est Ensemble region. This has led to the definition of the following objectives:

Table 1. Output of the SWOT + STEEP Analysis.

	STRENGHTS	WEAKNESSES	OPPORTUNITIES	THREATS
SOCIETY	S.S.1: Presence of mixed population groups S.S.2: Proximity to residential neighbourhoods	S.W.1: Homelessness S.W.2: Uninhabited areas S.W.3: Social imbalances	S.O.1: Multiculturalism and its promotion through artistic and musical activities	S.T.1: Conflicts and social degradation S.T.2: Difficulties of integration between different communities
TECHNOLOGY	T.S.1: Presence of urban agriculture association La Sauge T.S.2: Presence of specialised labour in industrial sectors	T.W.1: Scarce presence of tourist attractions T.W.2: presence of abandoned industrial areas T.W.3: Presence of old industrial buildings	T.O.1: Extension of the city on the canal with extension of services and facilities T.O.2: Connection to the geothermal heating network	T.T.1: Mass construction to meet housing demand resulting in gentrification T.T.2: Further degradation and abandonment of industrial areas
ENVIRONMENT	A.S.1: Vegetation along the area-boundaries A.S.2: Presence of the Canal de l'Ourcq A.S.3: Upgraded urban green areas A.S.4: Presence of natural interest areas	A.W.1: High traffic levels A.W.2: Presence of abandoned green areas A.W.3: Presence of industrial waste	A.O.1: Introduction of biodiversity awareness areas and life trails. A.O.2: Maintenance of La Sauge association A.O.3: Promotion of zero-impact agricultural production activities	A.T.2: Degradation and abandonment of green areas and vegetation along the canal

(*continued*)

Table 1. (*continued*)

	STRENGHTS	WEAKNESSES	OPPORTUNITIES	THREATS
ECONOMY,	E.S.1: Presence of industrial activities E.S.2: Presence of logistics centres	E.W.1: Brownfield areas with untapped economic potential. E.W.2: Single-functionality neighbourhoods E.W.3: Lack of services	E.O.1: Transport of goods along the canal E.O.2: Valorisation of empty spaces through active ground plans E.O.3: New hotel development	E.T.1: Non-activation of urban regeneration processes E.T.2: Difficulty in activating, urban regeneration processes for economic reasons and soil pollution
POLICY	P.S.1: Strategic location P.S.2: Presence Ecocité ZAC plans for redevelopment	P.W.1: Difficulties in implementing bureaucratic projects due to low participation	P.O.1: New T11 and TZen3 tram line stops, and new M5 metro line stop to connect with Paris	P.T.1: Expansion projects regardless of social impacts
MOBILITY	M.S.1: Dense public transport network at local scale M.S.2: River ports M.S.3: Proximity to CDG airport	M.W.1: No large-scale connection with Paris M.W.2: Lack of protected pedestrian M.W.3: Lack of cycle paths M.W.4: High noise pollution from rail traffic	M.O.1: Expansion of north-south transverse routes with canal bank connection M.O.2: Introduction of car-sharing and bike-sharing services	M.T.1: Strong increase in traffic along the main arterial roads and consequent increase in pollution

01. ENVIRONMENT: Improve the quality of public green spaces through interventions aimed at reducing noise and environmental pollution, reconfiguring the use of green spaces, and connecting existing parks. The interventions are oriented towards creating a network of paths and public green spaces that promote connection and cohesion.

02. CONNECTIONS: Improve the connectivity of the area, both from a physical-infrastructure and visual perspective. An effective and widespread system of connections allows for extending the opportunity to participate in the life and events of the neighbourhood to all individuals.

03. NETWORK: Enhance the functional offering present in the La Folle area and surrounding neighbourhoods. This objective not only aims to strengthen the existing



Numerical scale	Description
-2	The element in the row is strongly hindered, or even canceled out, by the element in the column.
-1	The in-line element is hindered by the column element, but nevertheless manages to develop its effects in a reduced form.
0	The elements in the row and in the column are independent.
+1	The element in the row increases its effects thanks to the synergy created with the element in the column.
+2	The in-line element significantly increases its effects thanks to the synergy with the column element.

Fig. 6. Comparison of Dynamic SWOT.

service infrastructure but also seeks to create an intricate network of connections and relationships that reconnect a previously fragmented territory.

From the definition of objectives and linking them to the results obtained from the SWOT + STEEP analyses, it has been possible to identify the main criteria to consider during the definition of the multicriteria analysis, aimed at outlining possible project scenarios.

3.4 Scenario Building

Building upon the state of the art identified through the SWOT + STEEP analysis, along with the objectives defined in Sect. 3.3, various alternative definitions of future scenarios have been developed.

To fulfil the aims of the network objective, the scenario envisages the redevelopment of a brownfield site through the construction of multifunctional buildings. While, for what concerns the environment and connections objectives, the proposed alternatives, in accordance with the specifications of the tender, includes:

- A scenario with 100% of the construction required by the tender.
- A scenario with 60% of the construction.
- A scenario with 40% of the construction.

These options stem from the intention to develop a design capable of addressing gaps and meeting identified needs during the exploratory phase through the SWOT + STEEP analysis. A key element in determining scenarios was the amount of sealed soil, with implications for the sustainability and environmental quality of the area under consideration.

3.5 Analytic Hierarchy Process (AHP)

The first step involved constructing a hierarchy diagram to define the project's objective and correlate it with the three previously identified alternative scenarios.

A crucial phase in this process was the selection and identification of criteria and sub-criteria to assess the three established scenarios.

In order to have a comprehensive comparison of the risks that emerged from the SWOT + STEEP analysis from the perspective of environmental, economic and social sustainability, the criteria in Fig. 7 were identified, including those related to environmental health, comfort, profitability and social fabric.

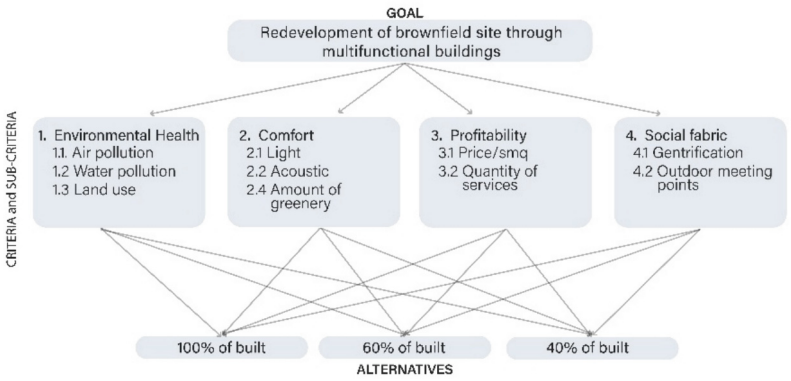

Fig. 7. Analytic Hiearchy Process (AHP) diagram.

After establishing the hierarchical structure, the subsequent process entailed pairwise comparisons using matrices. Firstly, all criteria were systematically compared with each other, followed by the comparison of subcriteria. Finally, each sub-criterion was compared in the AHP analysis within the context of the three land use alternatives of 40%, 60% and 100%. Subjective judgments were quantified using numerical ratings ranging from 1 to 9, assigned in ascending order of importance, as shown in Figs. 8 and 9. Throughout the comparative analyses, meticulous attention was dedicated to monitoring the level of inconsistency within the matrices, with a commitment to maintaining it below 10%.

ENVIRONMENTAL HEALTH is equally as important as COMFORT

ENVIRONMENTAL HEALTH	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	COMFORT

AIR POLLUTION is moderately more preferable than WATER POLLUTION

AIR POLLUTION	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	WATER POLLUTION

60% BUILT is very strongly to extremely more likely than 100% BUILT

60% BUILT	9	**8**	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	100% BUILT

Fig. 8. Example of pairwise comparison criteria, sub-criteria and alternatives.

After completing the analysis of pairwise comparison matrices, the optimal scenario has emerged, characterized by a preference for the option with a 60% construction rate, shown in Fig. 10. The definition of this scenario resulted from the weighted selection of evaluation criteria and sub-criteria, with particular attention to factors such as environmental health, comfort, and social cohesion. Additionally, economic implications related to the potential non-realization and funding of the intervention were taken into account. This decision aims to achieve a balanced compromise between environmental aspirations, comfort, and social justice, while simultaneously integrating the economic performance needs of the involved area.

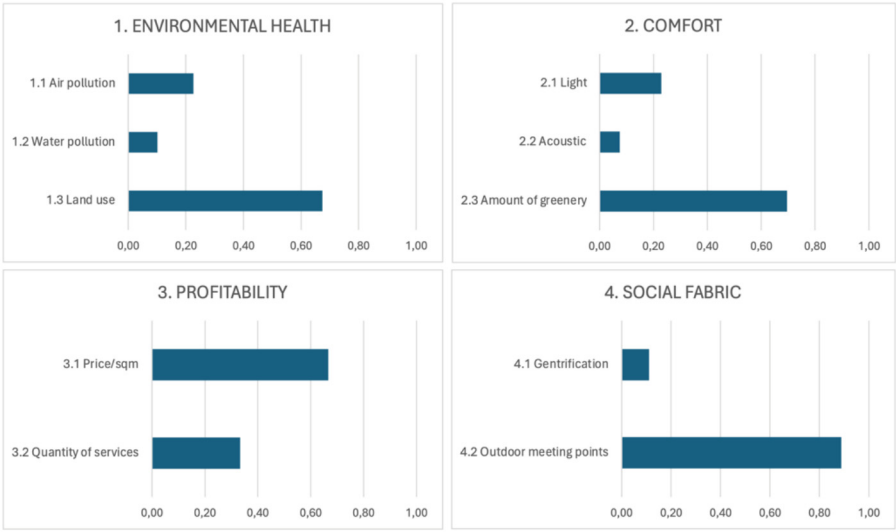

Fig. 9. Sub-criteria priority vectors.

4 Discussion

This paper investigates how a densification strategy for urban development can become more environmentally, socially, and economically sustainable through the support of the AHP analysis. The procedure relies on conventional assessment tools such as SWOT analysis and scenario building. It serves as an effective guide to orient the decision-making process towards sustainability in its various components.

The objective of the article is to highlight the intrinsic connection between infill development as a solution to urban sprawl, and its consequent soil sealing effects on the city. The Bobigny case study provides valuable insights into the importance of considering the urban densification process. Indeed, aspects such as ground coverage, building height, and their spatial arrangement emerge as crucial criteria for the success of smart growth approaches in reducing land occupancy and enhancing environmental quality, as well as soil permeability. The analysis does not delve into a detailed exploration of

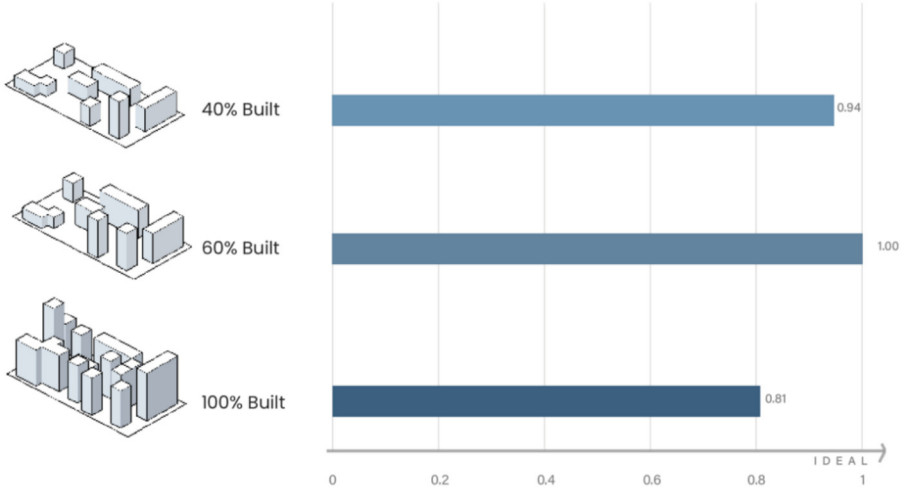

Fig. 10. Alternatives final ranking achieved for the case study.

building height and spatial arrangement, but rather focuses exclusively on determining a percentage of built area that copes with environmental and soil sustainability conditions.

In this paper, the building footprint is assumed to be 10 storeys equal for all constructions. Further analysis can be addressed to estimate the influence of an increasing number of storeys on the percentage of the built surface and its consequent implications on the environmental and comfort conditions. Moreover, spatial arrangement and site planning significantly influence the land occupancy. Yet these considerations were not addressed in the present study and may become the objective of further investigation once the percentage of soil occupancy derived from the current analysis is defined.

Furthermore, the sustainability of building construction also concerns construction methods, including materials used and construction techniques, factors not included in the analysis of the present study. It is crucial to ensure that the desired level of sustainability, established through the chosen soil percentage, is not compromised by factors such as the use of materials that contribute to an intensive pressure on the resources and the climate. The analysis primarily focused on the amount of occupied land and, as a result, criteria were established that address space at a total general level rather than specific details such as the selection of materials for building construction or materials that characterize ground pathways, which should be subject to more detailed analysis and investigation to ensure compliance with the concept of soil de-sealing addressed in the paper.

Finally, during the definition of criteria for the AHP analysis, it would have been useful to also consider how the space occupied by buildings and their use could influence the area's revitalization, considering the functions that would be integrated into the buildings and their long-term impact on the surrounding space. Evaluating the different building uses could have constituted additional sub-criteria, as different functions generate different economic profits.

5 Conclusions

This research highlights the importance of adopting a holistic and balanced approach in urban planning, which considers several interrelated factors. The proposed method, based on conventional evaluation tools such as SWOT analysis and Scenario Building, integrated with mixed approaches like Stakeholder Analysis, serves as an effective guide for sustainability-oriented decision-making processes. Through this methodology applied on Bobigny case study, it was possible to consider a wide range of criteria and weight them according to their relative importance, thus allowing an informed decision process. The analysis primarily focused on constructing and examining scenarios to understand which option could provide the best compromise between sustainability and profitability, with a primary consideration on land use. Information gathered during territory analyses, synthesized through a SWOT + STEEP approach, provided a robust foundation for the scenario building phase. During the analysis and evaluation phase, scenarios with varying degrees of land use were considered, relying on insights derived from the SWOT + STEEP analysis. In a maximal sustainability perspective, a scenario with reduced land occupancy would be preferred. However, the analysis underscored the importance of also incorporating profitability criteria into the AHP analysis to ensure economic feasibility and site redevelopment.

The strong correlation between the selected criteria is seen in the closeness of the results in the final ranking. Nevertheless, the analysis revealed that assigning too low of a percentage of built-up areas (i.e. 40%) could limit the opportunities for economic and social development in the area, while too high an allocation (i.e. 100%) could compromise the environmental quality, living comfort and social cohesion. In conclusion, based on these considerations, the scenario of 60% of built-up area emerged as the preferred option, striking a balance between environmental sustainability and economic profitability.

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Renewable Energy Communities: An Urban Capability-Based Approach to Evaluate Differential Participation in Cities

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Abstract. Renewable Energy Communities (RECs) are deemed to be capable of providing several benefits to their members, as well as to the area in where such associations operate. In this sense they could be considered as capable of expanding the Capability set of the inhabitants of a city to improve their individual and collective well-being. In this contribution, the Urban Capability approach is applied to the EU-introduced concept of RECs to evaluate the preference of different socio-demographic groups in translating RECs from capabilities to functionings. The proposed methodology aims to learn the preference model of individuals depending on their socio-demographic characteristics and geographical location, and to determine the correspondence between preference towards the performance of possible alternative RECs configurations across the city, and the performance thresholds set by inhabitants towards participation. The contribution also presents the questionnaire designed to operationalize the methodology and collect the necessary structured data to build a Machine Learning model able to learn individual preferences. Such structured data will also be used to enrich statistical data from census surveys to "spatialize" preferences related to socio-demographic characteristics of the population. Such types of data could have implications for policy makers in terms of allocation of resources and the evaluation of different levers to better support a wider and fairer participation of inhabitants to energy transition, while, at the same time, removing the barriers to achieve higher level of individual and collective well-being.

Keywords: Energy communities · Urban capabilities · Multi-Attribute Value Theory · Preference learning · Synthetic population

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1 Introduction

In Europe, the building sector is responsible for about 36% of energy related CO_2 emissions, and of 40% of its primary energy consumption [1]. Especially in residential sector, then, energy demand reduction by means of the application of energy-efficiency measures coupled with renewable sourced energy supply represent a major decarbonisation potential of energy uses [2, 3]. In such a context, civic participation is paramount in the achievement of the complex and challenging goal of contemporary society [4].

Among the citizen-led bottom-up initiatives, Energy Communities (EC) [5] are gathering more and more attention due to their capacity to integrate citizens as active actors in decentralized renewable energy generation [6–8], as well as in supporting more conscious way of consuming energy [9]. The aggregation of consumers in participatory schemes aims to take advantages of different building typologies as well as different shapes of consumption curves [10, 11] reducing the temporal mismatch between energy use and generation [12, 13].

At the European level, the Energy Community concept has been recently formalized in two distinct legal entities by the Renewable Energy Directive recast (REDII) [14], and the Internal Electricity Market Directive (IEMD) [15], both being part of the Clean Energy Package [16]; these two legal entities are the Renewable Energy Communities (RECs) and Citizens Energy Communities (CECs). Both concepts focus on the empowerment of the civil society in the energy market by allowing activities such as the production, storage, share and selling of energy produced by the members of such entities, with the former specifically bounded to the prescription of producing energy exclusively by using renewable sources. For such reason, this chapter focuses on this specific declination of possible Energy Communities.

Despite the European policy effort to integrate the civil society in the energy transition, currently, the transition towards the use of clean energy at the urban scale remains slow [17]. To evaluate the possible participation of individuals to the energy transition in the urban context and specifically through the deployment of RECs, this contribution will frame the participation to RECs within the Urban capability approach, viewing such participation as a particular state of functioning of individuals in cities.

Urban capability approach [18, 19] is used to study complex phenomena such as poverty and quality of life, to construct and evaluate public policies [20, 21], as well as to choose among possible feasible alternatives [18].

The capability approach identifies two fundamental aspects: functionings, and capabilities; the former being observable state of being (what a person is and do with her/his resources), and the latter the set of possible functionings that a person has access to. Specifically declined in the city context, urban functioning is what a person does or decide to be in the city, among the possible options (urban capabilities) at her/his disposal [22–25].

Furthermore, the set of available capabilities is determined by the interaction among individual capability (her/his intrinsic abilities) to be and to do, and the external condition (context) in which the individual operates [26]. As stated by Chiappero-Marinetti [20], the transformation of means in actual states is not a mechanistic process, but it is rather influenced by the plurality of intrinsic and extrinsic conditions; with the space being

a potential conditioning factor. In this sense the Capability approach imply the necessity to describe the real opportunities an individual has to use the city and to function autonomously and freely [27].

In the process of translating urban capabilities into urban functionings, we could argue that a fundamental aspect to be considered might be the actual system of value that an individual applies to determine what she/he considers as worth being [18, 28], considering individuals as fundamental agents in the transformation processes [29].

Finally, the Urban Capability approach might be of use to understand and describe those situations in which the interaction between city and inhabitants is suboptimal or expression of just a portion of the urban population [24, 27].

Being the participation to RECs able to generate different types of benefits (environmental, economic, social) to both its members and the areas in which these legal entities operate [14], such configurations represent a possibility for the inhabitants to expand their capability set, and increase the level of individual, as well as community well-being (Fig. 1).

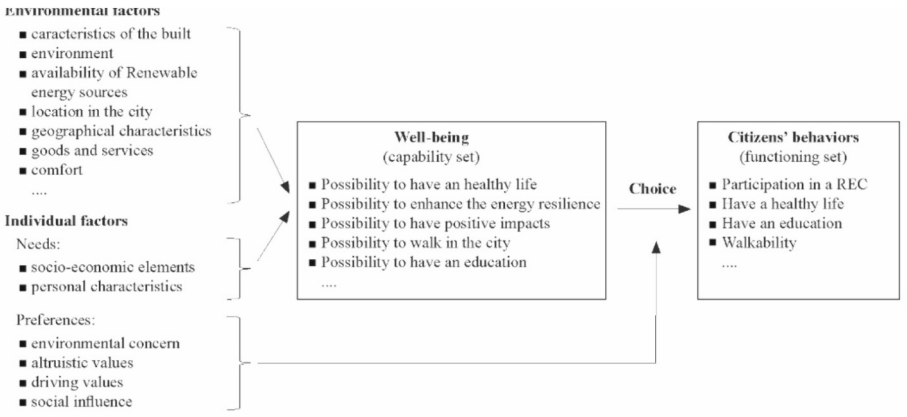

Fig. 1. Participation in a REC as an expansion of capability set (adapted from [28])

Considering the participation of the inhabitants of the city to RECs as possible functioning among the set of available conditions of individuals, this contribution aims at presenting a methodological framework to evaluate the willingness of civil society to participate in such associations as expression of their system of value, and, consequently, to evaluate the extent to which it could be expected that these configuration might be deployed in the urban context. Furthermore, such type of analysis might disclose asymmetrical and differential concretization of the REC concept within the urban fabric, exacerbating possible forms of peripheralization [30] and consequently the suboptimal achievement of the economic, environmental, and social benefits envisaged by the wide participation in RECs [14].

The rest of this contribution is structured as follows: In Sect. 2 the proposed methodology to evaluate civic participation as a declination of Urban Capability approach is

depicted, while in Sect. 3, its operationalization by means of a questionnaire to be distributed to city inhabitants is presented, together with the desired logical structure of the data to be gathered. Finally, in Sect. 4 some policy implications are discussed, while in Sect. 5, conclusions are drawn, as well as future applications of the proposed analysis.

2 Method

As stated, aim of this contribution is to set forth a methodological framework to evaluate the differential degree of civic society's participation in RECs, both spatially (in terms of spatial distribution of the willingness to transform the set of urban capabilities provided by different urban opportunities), and intrinsically, intended as the different inclination that specific group of individuals have toward the constitution of RECs. In order to do so, the proposed methodology is composed by three main parts. The first step (Preference analysis) is to evaluate individuals' system of value and thresholds in deciding either to participate or not in RECs based on socio-demographic characteristics. The second step (Synthetic Population) is meant to distribute the groups of individuals' system of values across the urban fabric by matching the socio-demographic composition of the parts of the city. Finally, by spatializing the socio-demographic groups' system of values (Spatialization) it would be possible to evaluate the likelihood of constitution of different possible configurations of RECs. The following of the section presents the different steps of the methodology in greater details, as well as the theoretical background supporting it.

2.1 Preference Analysis

Formally, the preference model of a user can be expressed by means of binary relations [31]. A binary relation $\succ_x$ among two elements of a set determines the preferability of one element over the other for a specific individual x. A binary relation on a set of elements Σ is a partial order if it is asymmetric

$$(a \succ b \Rightarrow \neg b \succ a),$$

and transitive

$$(a \succ b \wedge b \succ c \Rightarrow a \succ c).$$

A partially ordered set in which for every two elements of the set it exists a binary relation

$$(\forall u, v \in \Sigma : u \succ v \vee v \succ u)$$

is called totally ordered set [32]. The task of inducing a preference model that would result in the prediction of the order that the user would give to the elements of the set is called Label Ranking and has been particularly used to determine covariance between preferences and socio-economic information [33] in case of similarities among users [34].

In label ranking, given an instance x of an instance space X, and a finite set of labels $Y = \{y_1, y_2, \ldots y_k\}$, the aim is to learn a function that maps each instance x to a ranking $\succ_x$ over the set Y, where $y_i \succ_x y_j$ means that instance x (an individual) prefers label y_i to y_j. A ranking over the set of labels Y can be expressed as a permutation τ of {1, 2,…, c}, where $\tau(i)$ represents the position of label y_i in the ranking [35].

The order induced by the preference of x over Y could be explained in the framework of Multi-Attribute Value Theory (MAVT) developed by Keeney and Raiffa [36]. MAVT represents alternatives in a decision problem as composed by a set of attributes and interprets preferences by means of value functions associated with these attributes. The total value of an alternative is given by the sum of the marginal values for the attributes the alternative is composed of. Therefore, by means of aggregation criteria such as the additive one, it is possible to express the total value of the alternative u_y (1):

$$u_y(x) = \sum_{\beta=1}^{n} p_\beta u_\beta(x) \tag{1}$$

where u_β are marginal value functions associated to each attribute β that describe the alternatives, normalized between 0 and 1, and p_β represents the trade-offs among the attributes. In this way, we can define the preference of individual x over two objects as (2):

$$y_i \succ_x y_j \leftrightarrow \sum_{\beta=1}^{n} p_\beta u_\beta(x) >_x \sum_{\beta=1}^{n} p_\beta u_\beta(x) \tag{2}$$

Meaning that, the preference order expressed by x holds true if the total value of the most preferred alternative is greater than the total value of the less preferred one. To evaluate the preferences of individuals it becomes paramount, then, to estimate the shape of the value functions that the specific individual assign to each attribute that describes the different alternatives at his/her disposal.

In the operational research and artificial intelligence communities, the interest around learning and predicting preferences has grown [34], and, in recent years, Preference Learning (PL) has emerged as a branch of ML referring to the task of learning the preferences of individuals or classes of individuals from information about a set of items [37]. Roughly speaking, PL aims to induce preference models from data regarding explicit preference information [38], with a common attempt being to approximate the utility function of a decision maker in multi-criteria and multi-attribute settings.

PL has been widely used in several fields of applications (Fig. 2) such as prediction of customer design choices [39], travel modal choices [40], logistics, information retrieval, collaborative filtering [38]. Among the available methods, Additive Utility Functions (UTA) methods [41] take global statements upon set of alternatives, and subsequently infer the value functions that better fit such statements [28]. Based on linear programming, UTA method approximate value functions by minimizing the errors between the given preference structure over the set of alternatives, and the one computed by calculating the total values of alternatives given by the estimated value functions.

In the specific application that will be presented in Sect. 3, the decision over the participation in a REC has been defined by means of a vector of four attributes among those mostly used in the literature about feasibility analysis of Energy Communities (thus, considering Eq. (1), n = 4): (i) Investment Cost, (ii) Energy bills savings, (iii)

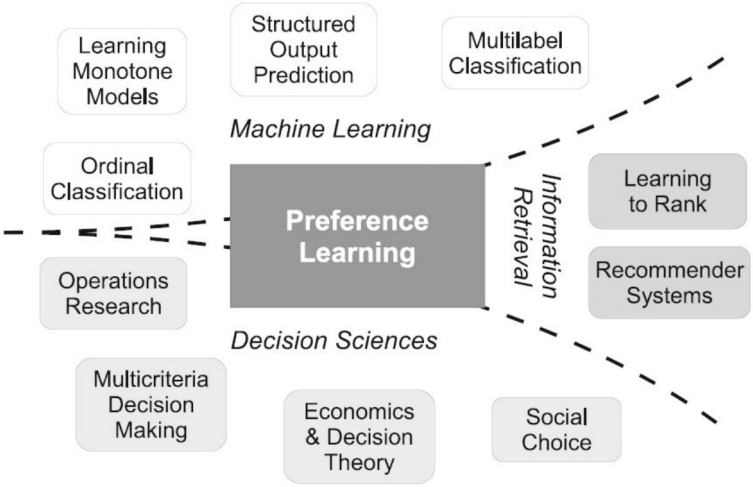

Fig. 2. Fields of applications of Preference Learning (source: [38])

Avoided greenhouse gas emissions, and (iv) Self-sufficiency index. These latter could be calculated relatively easily by means of Urban Building Energy Modelings (UBEMs) tools [42], and, therefore, the individuals' preference learned in this phase could be easily compared with performance data about possible scenarios of application of RECs in different parts of the city. The individuals' preferences are analysed (Sect. 3) by means of a questionnaire, in which the respondent is asked to perform an overall statement by declaring either if she/he is interested in participating in a REC defined by a specific vector of attributes (alternative $y_i \in Y \mid y = \langle \beta_{1i}, \beta_{2i}, \beta_{3i}, \beta_{4i} \rangle$) as well as to specify a complete order over the alternatives. By assigning different value functions (u_β) to the four attributes for each respondent satisfying Eq. (2), it would be possible to infer the preference model of each respondent.

2.2 Synthetic Population

To study the distribution of preferences across the urban environment, the use of population synthesis techniques is envisaged. Popular in the transportation research field, population synthesis refers to the process of creating a simplified microscopic representation of an actual population that matches the aggregated statistical measures of the actual population [43, 44].

To generate a synthetic population, a Population Synthesizer (the software that implement the process) requires two types of input data: disaggregate population samples referred as seeds, and population marginal distributions named as controls or targets [45]. By applying data fusion techniques, the synthetic population is generated expanding the seed sample to match the marginal distribution.

The population marginal distributions represent the constraints for the population synthesis procedure and might include social, demographic, and economic variables useful to describe the population living in a specific area under analysis (Census Block,

Census Tract, Metropolitan Statistical Area, or at any specified geography for which data are available).

The disaggregated data is typically obtained by census and other specific surveys to describe the population according to the goal of the study for which a synthetic population needs to be produced. The seed sample should contain demographic characteristics corresponding to the marginal control variables defined as controlled variables (age, sex, occupation, etc.), while it could also contain further information that are not controlled via the marginal distribution variables. Such variables, termed uncontrolled variables, could store the data enrichment of the seed sample by means of the value functions calculated in the previous step, thus allowing for the association of the preference models evaluated to the synthetic population modelled in each censor track of the urban environment.

Numerous are the software available to generate synthetic populations, among them, PopulationSim [45], is an open-source Python-based tool that is part of the collaborative framework ActivitySim [46]. Besides the seed tables, and the marginal distribution table defined via comma-separated values files, PopulationSim receives a further input (the Controls table) in the form of a logical map that connects the attributes from seed tables to marginal control ones [43].

The main output of the synthetic population is an artificial population whose distribution is coherent with the actual distribution of the real population living in a specified area (according to the availability of data of the marginal distribution, typically census track boundaries) with individual-level granularity of data according to the variables structure of the seeds.

Once the synthetic population has been generated, and the Value Functions for each socio-demographic group have been estimated with the UTA methods (step 1), it is possible to merge the two pieces of information by means of a data enrichment process. Data enrichment techniques are used when there is the need to enrich data from a dataset (referred to as *target* dataset), with information from another dataset (the *source* dataset) sharing a subset of common attributes. In the specific case, the target dataset to be enriched is represented by the synthetic population dataset generated, while the source dataset is represented by the questionnaire results, with the attribute to enrich the synthetic population with being the Value Function determined in step 1. The procedure used is taken from statistical matching algorithms [47–49]. In particular, a vector of attributes $A_{t,1:N}$ for each (target) observation t of the synthetic population, and one vector $A_{s,1:N}$ for the source dataset are defined, and the matching of the two is evaluated in order to append the Value Function information to the household h of the synthetic population dataset. The specific attribute to define the matching are determined based on the vector of households' socio-demographic attributes that determine the different shapes of Value Functions.

2.3 Spatialization

The third and final step of the methodology involves the evaluation of the matching degree between the performance of alternative RECs that could be established on the territory, and the preference models of the different socio-demographic groups across the urban environment by means of Geographical Information Systems (GIS) [50]. Municipality

GIS-based databases provide access to information regarding the urban fabric, allowing energy consumption evaluations, the assessment of renewable energy production options availability (considering also legal constraints), as well as the evaluation of possible energy efficiency intervention scenarios to be applied in different areas.

In this direction, the performance of possible alternative configuration of RECs across the city is calculated coherently with the range of attributes specified to determine and evaluate the preference model of inhabitants. By comparing the preference model of the enriched synthetic population generated with the performance achieved by different RECs alternatives in specific census tracks, it will be possible to determine the order of preference of the different socio-economic groups over the alternatives, as well as the thresholds posed by individuals to the possible participation in RECs. In Fig. 3 an expected result of this last step of the analysis is showed.

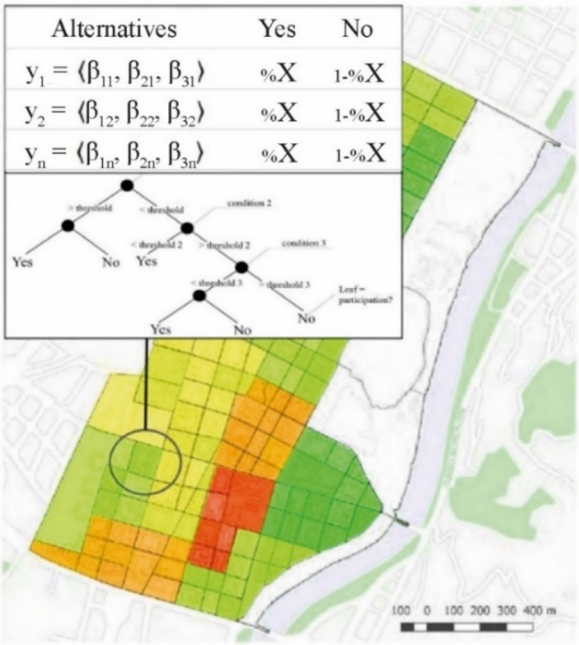

Fig. 3. Expected result of the Spatialization step (adapted from [44])

As showed in Fig. 3, for each census track, the final goal of the analysis is to determine the percentage of local population who, according to the approximated preference model, might be willing to participate in the possible alternative REC configurations *y* described as a vector of attributes β. Such analysis could provide useful information regarding the potential distribution of penetration of RECs in the urban environment depending on the typology and system of values of population that reside in a specific area (intrinsic capabilities), as well as on the contextual factor that might hinder such propensity.

3 Operationalization and Results

To operationalize the methodological architecture proposed in the previous section, a questionnaire has been constructed to gather the data necessary to define the individuals' preference model and the relevant socio-demographic variables that will be than used for the generation of the synthetic population. The following section is devoted to the presentation of the questionnaire and to show the structure of the output results from a pilot test run before its application to an Italian case study in the city of Turin (Northern Italy).

The proposed questionnaire has been constructed using the online survey tool limesurvey [50], and is composed by three main sections: (i) an introductory part devoted to a general set of questions based on a 4-point Likert scale on the themes of the research, in order to gather some introductory data regarding respondent's inclination toward RECs and their possible economic, environmental, and social benefits [14]; (ii) a second part in which the preference statements over respondent's willingness to participate in RECs are registered by means of a first filtering of possible REC alternatives, and two ranking exercises among the selected options; (iii) and a final part in which the socio-demographic data regarding the respondent and his/her household are collected. In Table 1 the logical structure of the questionnaire is presented.

For each question, the modalities define the available answers for the respondents. In this way, the first section of the questionnaire allows the respondents to specify his/her level of agreement with the specified statement on a 4-Point Likert scale, while the third section present modalities in terms of clusters (i.e., age = {<15, 15–19, 20–24, …, > 75 years old}, sex = {Male, Female, Other}, etc.) according to Italian census data [51].

As previously mentioned, in the second part of the questionnaire the respondent is asked to express a series of overall judgement on the alternative RECs proposed. As mentioned, the respondent is presented with 8 different REC alternatives described by means of four attributes: (i) investment cost, (ii) energy-bill savings, (iii) avoided CO_2 emissions, (iv) energy Self-sufficiency. For each of these alternatives, the respondent is allowed to state either if he/she would be willing or not to participate in the constitution of a REC with such characteristics, or if she/he is uncertain. In Fig. 4, an example of the question is displayed.

After this first filtering, the respondent is then asked to rank the alternatives for which she/he stated the willingness to participate or the uncertainty towards such decision. Hypothesizing a strict preference of the former over the latter, it is possible to extrapolate a complete order of the proposed alternatives for the generic respondent x. In Table 2 the results structure of a pilot test run is shown.

Together with the order of the alternatives useful for the approximation of the value functions by means of the application of the UTA methods, the clustering of alternatives in the "refusal to participate" category (when the respondent states his/her refusal to possible participation), allows to quantify the thresholds and total values of alternatives that determine their exclusion from the desired capability set of the respondent.

Table 1. Logical structure of the questionnaire

Section 1			
Code	Question	Modalities	Condition
1.1	Collaboration between people is essential to reduce energy consumption and all be more sustainable	4-Point Likert scale	
1.2	Reducing energy consumption is necessary to combat climate change	4-Point Likert scale	
1.3	Adopting energy efficiency measures in my home seems expensive to me, and it is not a priority for me	4-Point Likert scale	
1.4	Climate change can worsen social inequalities between people	4-Point Likert scale	
1.5	Promoting the well-being of all individuals is important, even if this may limit individual profit	4-Point Likert scale	
1.6	The State must commit to reducing society's environmental impact, including by introducing taxes to discourage the use of fossil fuels	4-Point Likert scale	
1.7	Are you already member of a REC	Y/N	
1.8a	Participating in the Energy Community has allowed me to reduce my impact on the environment	4-Point Likert scale	If 1.7 = Y
1.9a	Participating in the Energy Community has allowed me to have a positive impact on my quality of life and that of other people as well	4-Point Likert scale	If 1.7 = Y
1.10a	Participating in the Energy Community has allowed me to save on my energy bill	4-Point Likert scale	If 1.7 = Y
1.11a	Participating in the Energy Community has allowed me to be less dependent on changes in the price of energy	4-Point Likert scale	If 1.7 = Y
1.11a	Participating in the Energy Community required a significant initial expense	4-Point Likert scale	If 1.7 = Y
1.8b	I am interested in the social benefits that an Energy Community can guarantee for families in economic difficulty	4-Point Likert scale	If 1.7 = N

(*continued*)

Table 1. (*continued*)

Section 1			
Code	Question	Modalities	Condition
1.9b	I am interested in the savings on my energy bill that an Energy Community can guarantee	4-Point Likert scale	If 1.7 = N
1.10b	I am interested in the reduction of polluting emissions that an Energy Community can guarantee by producing clean energy or reducing consumption	4-Point Likert scale	If 1.7 = N
1.11b	I am interested in the possibility of self-producing part of the energy I consume in order to be more self-sufficient	4-Point Likert scale	If 1.7 = N
1.12b	If I decided to become a member of an Energy Community, I would also be willing to invest money	4-Point Likert scale	If 1.7 = N
Section 2			
code	**Alternative selection**	**Modalities**	**Conditions**
2.1–2.8	Would you participate in a REC option (y)? (With $y \in Y$, and $Y = \{A, B, C,\ldots,H\}$)	Yes/No/Maybe	
	Ranking		
2.9	Rank the options you stated you would agree to participate in	Complete order	$\forall y \in Y, \mid \langle y,\text{Yes}\rangle$
2.10	Rank the options you stated you might agree to participate in	Complete order	$\forall y \in Y, \mid \langle y,\text{Maybe}\rangle$
Section 3			
code	**Question**		**Modalities**
3.1	Sex		2 modalities
3.2	Age group		13 modalities
3.3	Educational level		5 modalities
3.4	Profession		10 modalities
3.5	Citizenship		2 modalities
3.6	Household size		7 modalities

(*continued*)

Table 1. (*continued*)

Section 1			
Code	Question	Modalities	Condition
3.7	Questions 3.1 to 3.5 for each member of the household (as stated in 3.6)		-
3.8	Property regime of the household		2 modalities
3.9	Annual income of the household		5 modalities
3.10	Who has more influence on household decisions		4 modalities
3.11	Household location		Pin on map

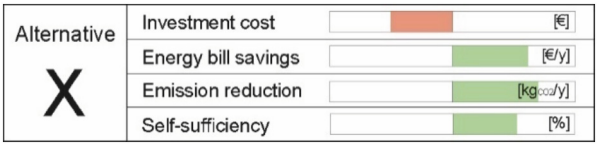

Fig. 4. Example of tabular description of a REC alternative

Table 2. Structural logic of the results of the pilot test

ID	Alternative (0 = No, 1 = Maybe, 2 = Yes)								Order	
	A	B	C	D	E	F	G	H	Yes	Maybe
1	2	2	2	2	2	2	2	2	E, B, D, C, A, H, F, G	
2	0	0	2	0	2	1	1	2	H, C, E	G, F
3	1	0	0	2	0	0	0	0	D	A
4	1	0	2	0	1	0	1	0	C	A, E, G
5	2	2	2	2	2	2	2	0	A, D, E, B, C, F, G	
6	0	1	0	0	0	1	2	0	G	F, B
7	1	0	1	1	1	1	0	0		A, C, D, E, F
8	2	0	0	0	0	0	0	1	A	H
9	2	0	2	0	2	0	0	0	A, C, E	

4 Policy Implications

The academic production on RECs mainly focuses on energy planning aspects related to technical feasibility, often neglecting to consider other mostly social aspects in the evaluation of possible configurations of RECs [52]. This latter aspect reinforces the concept of a difficult integration between energy planning and city planning [53, 54].

Sustaining the necessity to consider the integration of RECs into urban planning as part of the "enabling framework" that the Member States should provide according to European Directive RED II, Gerundo & Marra [55] propose a methodology for the prioritization of areas where the public decision makers could intervene to maximize energy and social benefits with the minimization of constraints on the formation of RECs. Among the social benefits that this methodology aims to maximize, is the one related to energy poverty alleviation [16, 56]. Even though there is no single conceptualization on how to quantify energy poverty, several proxy variables are commonly used to identify this condition, such as poor energy performance of housing, high ratio between energy expenditure and income, and low-income inhabitants [55, 57].

It has already been stated that an effective strategy for reducing energy poverty is to encourage area-based initiatives, i.e., to intervene where there is greater need [58]. In this direction the overlapping of different layers of information (such as urban plan constrains and areas of low performing residential dwellings as proposed in [55] methodology) could benefit from the integration of two other pieces of information that are considered in the proposed methodology in this contribution. First, the evaluation of potential performance of alternative RECs configurations in different areas will highlight the limitation posed by the actual morphology of the city that individuals interested in distributed generation from renewables and energy efficiency intervention projects will face (considering the specific location in the different part of the city as a potential source of inequality, both from the point of view of capabilities, and intrinsic condition of the urban fabric). Second, the matching degree between the possible achievable outcomes of different RECs configuration and preference models of the population will shed light on the expectable magnitude of bottom-up initiatives that could arise from the territory, and the degree with which these could meet the public goal of reducing greenhouse gases emission from the urban environment.

In light of this level of information, the public authority could consider forms of intervention to increase its support both financially (such as financial schemes to support fragile socio-demographic groups [59]), or by direct intervention by considering entering RECs with public own buildings [60], by easing the extent of constrains posed by the urban planning use of land, or by supporting the participation of third entities such as ESCOs to partner with groups of individuals residing in less wealthy areas.

A further aspect worth considering is the potential effect of energy poverty alleviation and emission reduction on health and well-being of the population, supporting the necessity of providing decision makers with a clear mapping of the areas that, due to the limiting factor highlighted, would not be able to self-sustain a fair ecological transition.

5 Conclusions and Future Perspectives

In this contribution, the Urban Capability approach has been applied to study the possibility for urban inhabitants to participate in Renewable Energy Communities as a potential conversion of the capability set in Urban functionings. In such an effort, to consider the preferences of different socio-demographic groups is paramount to evaluate the system of values that could result in the willingness to participate in such associations, or in the refusal to act in this direction.

The proposed methodology composed in three steps (analysis of different socio-demographic groups preferences, construction of a synthetic population enriched by data regarding people's system of values, and the spatialization across the urban environment) could shed light on the real potential penetration of the REC concept among different strata of the population, and urban geographies depending on intrinsic characteristics of the population, as well as on resource availability of the territorial context.

The methodology will be applied to a real case study in the city of Turin (Italy). The expected results might have several policy implications in the effort toward the energy transition, conceived as an occasion to reduce inequalities in the urban environment. First, the spatialization of the likelihood of RECs constitution might support the public Decision-Maker in defining policies that might aid the more fragile part of the population in embarking in such projects as an attempt to reduce peripheralization effects highlighted by a slacking attention towards the less appealing areas [61, 62] Second, possible suboptimal outcomes in terms of mismatch between the economic oriented private Decision-Maker preferred alternatives and the Public Interest most preferred ones could be highlighted, and corrective measures undertaken. Furthermore, possible spaces for partnerships might be envisage for those areas in which the establishment of a REC might have substantial direct or undirect benefit for the population wellbeing, even though the inhabitants are not interested or uncapable to undergo such types of investments, potentially resulting in a waste of resources (firstly spatial resources in case of distributed renewable energy generation). Finally, in case of areas of low level of interest shown by the living population, these might be targeted by specific participatory processes that the Public Authority might put in place to further examine the reasons behind the population indifference or refusal (or even impossibility) to act.

An additional expansion of the research could be seen in the possibility to replicate the study in different cities: the distribution of the questionnaire in other locations will allow to look for pattern of homogeneity regarding the preference model of socio-demographic groups in different geographic areas and to identify specificities in the potential penetrations of the RECs concept depending on the variation of the intrinsic and extrinsic capabilities in those areas. This latter would represent a source of information for the public Decision-Makers to monitor the effect of the policies supporting the REC strategy to foster the sustainable green transition.

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Enhancing High-Speed Train Line Design: The Role of Multidimensional Assessment Tools

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Abstract. Decision-making in complex environments, such as the implementation of high-speed railway networks, requires a comprehensive approach considering diverse criteria and stakeholder perspectives. This paper presents a model for evaluating alternative scenarios in a multidimensional manner to support Decision-Makers (DMs) in making informed choices. Drawing on the Italian context, where high-speed rail networks have been successfully implemented, the study emphasizes the need for a systematic framework to assess socio-environmental impacts and technical-economic considerations. The proposed model integrates Multicriteria Decision Analysis (MCDA) to provide a structured approach for comparing alternatives based on various criteria, including social, environmental, and technical-economic factors. Through a detailed analysis of the decision problem, the model identifies fundamental objectives and instrumental criteria, reflecting the interests and priorities of stakeholders. A systematic evaluation process, including problem structuring, criteria measurement, weighting, and aggregation, enables DMs to assess each alternative's performance comprehensively. Adopting such a multidimensional approach makes understanding the trade-offs involved and making more informed and sustainable decisions regarding high-speed railway network implementation possible. This framework promotes transparency, stakeholder engagement, and equitable distribution of benefits, ultimately facilitating the achievement of broader societal goals.

Keywords: Multicriteria Decision Analysis (MCDA) · Complex decision problems · Stakeholders values

1 Introduction

High-speed trains represent a pivotal advancement in modern transportation, offering several benefits that extend far beyond the mere rapidity of travel [1, 2]. These infrastructures not only revolutionize the concept of traveling but also address some of today's most pressing challenges, ranging from environmental concerns to accessibility and territorial equity [1].

One of the primary benefits of high-speed trains is the promotion of accessibility. Thanks to their speed and efficiency, they allow people from diverse regions to connect quickly and easily, drastically reducing travel times compared to conventional modes

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of transportation. This is particularly significant for rural and peripheral communities, previously isolated or difficult to reach, which can now enjoy greater accessibility to urban centers, services, and opportunities. Another positive benefit concerns the reduction of car usage. By providing a convenient and efficient alternative to road transport, they encourage a decrease in vehicular traffic, reducing greenhouse gas emissions and atmospheric pollution. This positive impact on the environment contributes to the climate change issue by promoting public health, improving air quality, and reducing dependence on fossil fuels [3].

However, despite these evident benefits, some concerns arise regarding territorial equity. Specific communities, especially those outside the routes of high-speed trains, may feel excluded from these advanced connections. This disparity could exacerbate socio-economic and geographical inequalities, limiting access to job opportunities, essential services, and infrastructural development. Addressing these challenges requires strategic policies not to worsen regional gaps [2].

Focusing on the Italian context, high-speed trains have emerged as an example of the successful implementation of the transformative mode of transportation [4]. Italy boasts an extensive high-speed train network connecting major cities and regions nationwide. This network links vital urban centers such as Milan, Rome, Florence, Naples, Turin, and various regions. Introducing high-speed trains in Italy has yielded economic and environmental benefits [5]. These include i) reduced travel times between major cities, enhancing connectivity and facilitating business and leisure travel; ii) economic growth, fostering tourism, facilitating trade, and attracting investment to regions along the network; and iii) environmental sustainability, offering a more sustainable mode of transportation compared to air and road travel, resulting in reduced carbon emissions, and mitigating environmental impact [6].

Despite their benefits, high-speed trains in Italy face several challenges, including i) infrastructure investment; sustaining and expanding the high-speed rail network requires substantial investment in infrastructure development and maintenance, posing financial challenges for policymakers; ii) accessibility disparities; rural and peripheral regions may experience limited accessibility, exacerbating socio-economic disparities and iii) environmental concerns regarding their energy consumption and potential ecological impact, particularly during construction phases [7, 8]. It is relevant to underline all the significant achievements and to face all the challenges properly to ensure long-term success and equitable distribution of benefits.

Within this context, designing and implementing high-speed train lines requires a comprehensive approach that considers diverse factors and stakeholders' perspectives and evaluates potential alternatives effectively [9]. Such methodologies are crucial for integrating tangible and intangible criteria [10] and accommodating conflicting opinions and values among stakeholders involved in the decision-making process [11, 12]. The adoption of multidimensional support tools, i.e., Multicriteria Decision Analysis (MCDA), as demonstrated by other researchers [13–17], offers significant advantages over traditional Cost-Benefit Analysis (CBA) for evaluating complex and multi-stakeholder issues [18–20]. By enabling a holistic assessment that considers diverse criteria and stakeholder perspectives, MCDA enhances the decision-making process, leading to more informed and sustainable outcomes [21].

The present paper aims to provide a model to support decision-makers (DMs) in comparing alternative scenarios to implement the existing high-speed train network in Brescia (Italy) by considering a multidimensional perspective. The framework proposed is based on the MCDA methodology, and the criteria defined are coherent with the decision problem investigated.

The paper is divided into four sections: after the introduction (s1), the methodology is presented (s2), the evaluation framework is structured (s3), and limits and future perspectives are discussed in the conclusions (s4).

2 The Role of the Multicriteria Decision Analysis (MCDA)

MCDA serves as a systematic and robust framework for decision-making in complex environments where multiple criteria need to be considered [22]. When a mono-criterion approach cannot catch the complexity of the problem to be solved, or an economic evaluation is insufficient to analyze different values in play, the MCDA becomes a strategic approach to be adopted [23]. Among the other strengths:

- MCDA considers various factors, including economic, environmental, social, and technical aspects, ensuring a thorough analysis;
- Complex decision problems, such as those analyzed within this contribution's context, entail quantifiable metrics (e.g., cost, travel time) and qualitative considerations (e.g., social impacts, cultural heritage preservation). Multidimensional assessment tools allow for the integration of these tangible and intangible criteria into the decision-making process, ensuring a balanced evaluation [24];
- Stakeholders involved in complex problems often have divergent interests and priorities. MCDA provides a structured framework for eliciting and incorporating stakeholders' opinions and values. By facilitating transparent communication and consensus-building, these tools help understand conflicting perspectives and enhance stakeholder engagement [20].

MCDA also presents some criticalities. Compared to the stated preferred methodologies, it is not suitable to catch the preferences of individuals across the whole population [25]. Moreover, accepting qualitative information could cause uncertainty and ambiguity [26]. Also, the weighting is open to criticism, especially in interpreting the meaning of the weights [26]. In this context, the sensitivity analysis and the selection of the most appropriate weighting and aggregation procedure aim to verify the robustness of the results [26].

2.1 MCDA Main Phases

The MCDA is structured in several phases (Fig. 1), which allows for breaking down complex problems into more straightforward steps and focusing on specific tasks to obtain a more conscious understanding of the context and decide [27, 28].

In the first phase, it is possible to recognize the problem structuring, where the boundaries of the decision context are set, objectives and criteria relevant to the decision problem are identified, and feasible alternatives or courses of action available for

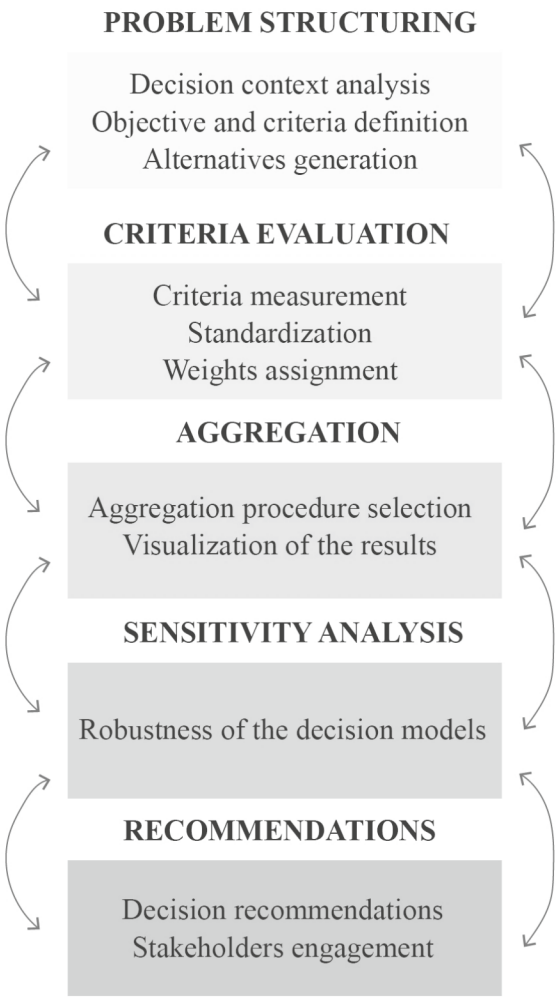

Fig. 1. Methodological framework.

addressing the decision problem are generated. The objectives should encompass all dimensions of the decision-making context and reflect the stakeholders' interests and priorities.

In the second phase, the criteria measurement is processed; once the objectives and alternatives are established, it is possible to assess the performance of each alternative against the identified criteria. This entails measuring how each alternative satisfies or achieves the specified objectives. To compare alternatives and aggregate the scores calculated, the next step involves standardization, where criteria lose their specific unit of measurement to acquire a standard a-dimensional scale, usually between 1 and 0 (where 1 represents the best performance while 0 is the worst). After that, weights can

be assigned to the criteria based on their relative importance or significance in achieving the overarching objectives [29]. The weighting process ensures the evaluation is appropriately balanced and reflects the stakeholders' preferences. In the third phase, standardized scores and assigned weights can be aggregated using the most appropriate procedure (i.e., choice, raking, and clustering) [30].

Moreover, different methodologies for addressing complex choice problems exist depending on the research objective, criteria, and the desired outcome. The main ones are i) the compensatory methodology to assess the trade-off (compensation) between criteria and ii) the non-compensatory, through which the more complex interaction between criteria can be considered. Once the most suitable aggregation procedure has been selected and the results visualized, it is possible to move to phase four, where the sensitivity analysis assesses the reliability and robustness of the decision model; this involves examining how changes in the input parameters, such as criteria weights or performance scores, affect the final decision outcomes. The last phase consists of recommendations; based on the analysis results, DMs derive recommendations or decision insights to guide the selection of the most suitable alternative. These recommendations are communicated to stakeholders to facilitate informed decision-making [31].

The model is flexible and iterative, and each phase could be reviewed if the results are unsatisfactory [32].

3 A Proposal to Assess High-Speed Train Line Alternatives

The assessment framework defined to compare design alternatives was developed based on the specific needs of the new intervention to be implemented in Brescia (Italy). The overall framework will be presented within this context since the application has yet to be concluded. Given the multidimensionality of the decision problem, fundamental objectives (thematic areas) were identified as a first step, subsequently articulated into instrumental objectives (criteria) [33], which allow the problem to be analyzed in its complexity, considering aspects of a social nature, relating to the potential change in the welfare of those affected by the infrastructure expansion projects; aspects of an environmental nature concerning acoustic impacts and on the quality of resources, such as air and soil; as well as aspects of a techno-economic nature, referring to the technical characteristics of the two expansion hypotheses, site management and production costs. The decomposition of the problem and the definition of a multidimensional value tree allow the areas to be compared and evaluated both partially, considering the thematic area of reference, and globally, thus aggregating the different performances.

The decision-making framework is the result of several meetings with key stakeholders. It, therefore, reflects interests consistent with both the goals of the municipal administration and the needs of the society and proponents of the initiative.

Analyzing the problem and considering the public perspective in detail leads to an overall objective more focused on environmental and social aspects, resulting in the *"Definition of the most suitable alternative able to maximize socio-environmental benefits."*

3.1 Potential Negative Impacts

The construction of new railway infrastructure can bring significant benefits to transportation networks, but it also poses challenges for local communities, particularly those near construction sites [34]. Railway construction activities, such as noise, dust, and vibration from heavy machinery, can disrupt residents' daily lives near construction sites. These disturbances may affect sleep patterns, increase stress levels, and diminish overall quality of life [35]. The influx of construction vehicles and temporary road closures can lead to increased traffic congestion and safety hazards for residents. Detours and traffic diversions may disrupt regular commuting routes and access to essential services [7].

Moreover, railway construction projects frequently require expropriating and demolishing properties along the route. Residents may be forced to relocate, leading to the loss of neighborhood cohesion. Property expropriation and demolition can cause economic displacement for affected residents, particularly if they cannot secure fair compensation or suitable alternative housing [36]. This displacement may exacerbate existing socioeconomic inequalities within the community [37]. Addressing these challenges requires careful planning, community engagement, and mitigation measures to minimize disruptions and ensure that affected residents are adequately supported throughout construction [38].

3.2 The Evaluation Framework

With the overall goal of supporting the choice of the solution that maximizes socio-environmental benefits, in consideration of the co-presence of different objectives, expressing the needs and expectations of the main stakeholders, and keeping in mind the potential adverse effects, the decision problem was decomposed into three thematic areas, further detailed into criteria and sub-criteria.

The evaluation framework has been conceived and structured by analyzing all the possible issues that could emerge from implementing a railway system (Table 1). Criteria, sub-criteria, and the potential indicators useful to measure the performance of the alternatives have been defined starting from workshops organized together with the main stakeholders involved in the analysis and verified with an investigation of the literature review on this topic. Mainly to check the robustness of the proposed framework, a literature review focused on the MCDA methodology and the implementation of the railway system has been developed, resulting in several existing research studies on this topic [35, 39–52]. Table 1 reflects the synthesis of the phases processed.

For each thematic area, it is essential to define the overall objective to be met and to prepare an evaluation form with three parts:

- General objective: underlying the choice of criterion;
- Performance score: describing the method of evaluation and the unit of measurement;
- Performance evaluation of alternatives: where the rating/ score for each performance is presented.

Table 1. Evaluation framework

Thematic Areas		Criteria		Sub-criteria	
1	Social	1.1	People involved/Propensity for relocation of potential people subject to expropriation	1.1.1	Socio-economic profile (age, households, family composition) of the inhabitants subject to expropriation (owners/tenants)
				1.1.2	Inhabitants subject to construction site impacts
		1.2	Properties involved	1.2.1	Type and number of housing units subject to expropriation
		1.3	Visual impact during construction and post construction	1.3.1	Assessment of the visual impacts generated on the buildings present by the 10 m buffer zone from the construction site fences
				1.3.2	Assessment of the visual impacts generated on the buildings present by the 10 m buffer zone from the railroad walls
2	Environmental	2.1	On-site and post construction vibration	2.1.1	Evaluation of vibration impacts generated on the buildings present from the 10 m buffer zone from the construction site fences (day and night)
				2.1.2	Assessment of vibration impacts generated on the buildings present from the 10 m buffer zone from the railway walls (day and night)

(*continued*)

Table 1. (*continued*)

Thematic Areas		Criteria		Sub-criteria	
		2.2	Noise at the construction site and post-work	2.2.1	Assessment of the acoustic impacts generated on the buildings present from the 10 m buffer zone from the construction site fences (diurnal)
				2.2.2	Assessment of acoustic impacts generated on buildings intersected by the 10 m band from railway walls (day and night)
		2.3	Dust	2.3.1	Evaluation of dust impacts generated on buildings present from the 10 m band from the construction site fences (day and night)
		2.4	Traffic	2.4.1	Traffic interference in accessing the units
		2.5	Land	2.5.1	Land consumption balance
3	Technical Economic	3.1	Time	3.1.1	Duration of the construction site in the reference area
				3.1.2	Impact of the construction site on the overall project
		3.2	Interference on rail service	3.2.1	Effects on the quality of rail service
		3.3	Total implementation costs	3.3.1	Estimated cost of works
				3.3.2	Estimated costs and compensation inhabitants (owners/tenants)

3.3 Evaluation Criterion

Below, some examples of an evaluation criterion form are proposed to show how the analysis will be further developed and structured.

The Criterion *"1.3 Visual impact during construction and post-construction"* considers the alteration of any natural or urban landscape with the inclusion of elements that, by their extraneousness, modify and negatively impact the reference context with effects on the population affected by such intervention. The criterion aims to minimize such effects.

The general objective of the sub-criterion *"1.3.1 Assessment of the visual impacts generated on the buildings present by the 10 m buffer zone from the construction site fences"* is to assess the impact of construction site fencing on residents living in buildings located near the project area. The performance score is assigned by considering the free-view index, which represents the distance (d) ratio of individual building façades with the construction site fences and the height of those façades (line). An average of the indices obtained between the distance of buildings and construction site fences was calculated for the evaluation. The distances of the façades to other properties were not captured as they do not change in the different alternatives due to the presence of the project. An index of 1 represents an optimal distance; conversely, an index of 0 is critical.

The Criterion *"2.5 Land"* assesses land consumption, associated with the loss of a critical environmental resource. The process is mainly due to constructing new buildings and infrastructure, expanding cities, densifying and converting land within an urban area, and land infrastructure.

The sub-criterion "2.5.1 Land consumption balance" aims to evaluate the presence of vacant areas that could be used as green areas and the enhancement of the existing bicycle and pedestrian pathways. The performance score is assigned considering a qualitative scale where:

- "high" represents the presence of vacant areas in continuity with the pedestrian-cycleway;
- "medium" is the availability of the vacant areas only;
- "low" is the absence of vacant areas.

The next step of the evaluation form consists of measuring the performances of the alternatives generated.

4 Conclusions

The present contribution highlights the strategic role of multidimensional assessment tools in designing and implementing high-speed train lines effectively. By integrating tangible and intangible criteria and accommodating stakeholders' perspectives, MCDA enhances decision-making, leading to more informed and sustainable outcomes. MCDA encompasses a structured and rigorous approach to decision-making, comprising several critical phases from problem structuring to decision support and interpretation. By systematically evaluating alternatives against multiple criteria and engaging stakeholders throughout the process, MCDA facilitates informed and transparent decision-making in complex decision environments.

The paper presents a framework based on MCDA to support DMs in evaluating alternative scenarios for high-speed train network implementation in Brescia, Italy. The framework encompasses social, environmental, and technical-economic criteria, providing a structured approach to assess the socio-environmental impacts of railway projects.

By adopting such methodologies, DMs can ensure equitable benefits distribution and address the affected communities' concerns.

From the analysis, it emerges that beyond the positive impact brought by the implementation of accessibility, several issues have to be faced. While railway construction projects may present significant challenges for local communities, proactive planning and stakeholder engagement can help mitigate adverse impacts and ensure that affected residents are adequately supported throughout the construction process. By addressing concerns related to property expropriation, noise and vibration, traffic disruption, environmental protection, and social support services, railway authorities can foster positive relationships with local communities and enhance the overall sustainability of construction projects. The proposed model can support the definition of coherent strategies to overcome those challenges and select an alternative to minimize potential criticalities.

Concerning the limitations of the contribution, the proposed model and evaluation framework are tailored to the context of high-speed train network implementation in Brescia, Italy. While it provides valuable insights into decision-making processes for this case, its applicability to other contexts or regions may be limited. Different areas may have unique socio-economic, environmental, and technical considerations that require customized approaches. Moreover, the model's effectiveness heavily relies on the availability and reliability of data for criteria measurement and evaluation. In some cases, obtaining accurate data, especially regarding social and environmental impacts, may be challenging. Data quality and consistency across different sources could affect the robustness of the evaluation outcomes.

Considering the possible future steps, after applying the methodology to the analyzed project, conducting pilot studies or case studies in different contexts can help validate the model's effectiveness and identify areas for improvement. Iterative refinement of the framework based on empirical evidence and stakeholder feedback can enhance its applicability and robustness across diverse settings. For the data issue, incorporating advanced technologies such as remote sensing, GIS mapping, and participatory sensing can provide real-time insights into social and environmental impacts, enabling more accurate assessments. Moreover, it could be successful to establish mechanisms for long-term monitoring and evaluation of implemented projects to assess their actual socio-economic, environmental, and technical outcomes. Incorporating feedback loops into the decision-making process to iteratively improve future project designs and management strategies based on lessons learned could be a keystone.

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MaaS Solutions for Airports, Cities and Regional Connectivity (MaaS 2024)

Application of Geospatial Analysis to Tourist Flows in the Insular Destinations

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Abstract. Tourism is one of the main growing sectors in the global economy bringing new opportunities associated with the transportation offer. The Covid -19 health crisis, which caused a major shock in tourist flows, also represents the main "*watershed*" for the evaluation of any changes that occurred in the tourism development model and its destinations. In Italy - including the islands - there is a significant recovery in tourist flows post Covid-19. In this framework, the objective of the paper is to develop a methodological approach based on geospatial analysis to evaluate the spatial distribution of tourism flow in Italian insular contexts. In this sense, the Sardinia Region in Italy represents an interesting case study to analyze tourist destinations related to air and maritime traffic (pre and post Covid-19). The manuscript, which is part of the "e.INS – Ecosystem of Innovation for Next Generation Sardinia", supports the construction of the airport MaaS concept, to better organize the transport offer in the insular context, enhancing sustainable mobility.

Keywords: Geospatial Analysis · Tourism Destinations · MaaS

1 Introduction

The European tourism industry is recovering after Covid 19 [1, 2], also due to the increase in passenger traffic, arrivals, and presences [3] - short and long trips - in tourist destinations, diversified experiences and attention to sustainability and technology. Knowing these trends will be critical for destinations to adapt and meet the evolving needs of modern travelers. According to data provided by Enit - National Tourism Agency, with Human Company and Istituto Piepoli, 65% of Italians stay in Italy for their holidays, revealing a predilection for the sea, followed by cultural holidays and stays in the mountains. Digitalization, sustainability, and personalized offerings have become key factors in attracting and retaining customers. Local governments play a crucial role in promoting sustainable tourism by regulating the market for private hospitality homes and improving public transport to increase the accessibility of tourist destinations [4, 5]. In particular, air transport in Italian insular contexts is a growing sector with great potential [6]. However,

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in order to fully exploit this potential, some challenges need to be addressed, such as seasonality in the broader framework of the different models of air territorial continuity [7–9].

The Italian air traffic is exceeding pre-pandemic levels by 11%, thanks to the progressive return to travel for various reasons [10, 11]. The drivers of the great recovery in national air traffic were above all medium and small airports [12], many of which even exceeded 2019 levels. These include the airport system of the Sardinia Region, an Italian island, with the following three airports: Cagliari - Elmas (CAG), Olbia - Costa Smeralda (OLB) and Alghero (AHO), which are the main hubs of the related airport regions (geographical areas characterized by different levels of connectivity with airport infrastructures).

In this framework, the objective of the paper is to develop a methodological approach based on geospatial analysis (Kernel Density Estimations - KDE and Local Indicator Spatial Autocorrelation - LISA) to evaluate the distribution and spatial characteristics of tourism flow in Sardinia Region, highlighting traffic patterns among the local airports and related destinations.

Considering the pandemic as a "watershed" between two moments (pre and post Covid-19), the manuscript analyzes data relating to arrivals, presences, and departures of passengers (short and long trip), in the period between 2019 and 2022 to assess whether elements of continuity or discontinuity can be recorded with respect to the past development trend of the tourism sector.

The results are functional to guide future policies and actions to promote sustainable transport models, especially in connections to and from airports in the regional context, in line with the concept of Mobility as a Service (MaaS) [13].

The manuscript is organized as follows: Sect. 2 - Materials, data and method, provides a description of the study area, the dataset to support geospatial analysis of tourism flows in Sardinia and the methodology; Sect. 3 - Results, discusses the main results of the spatial analytical techniques used to analyze the dynamics of tourist flow; Sect. 4 - Conclusions, proposes possible development in the research field.

2 Materials, Data, and Method

2.1 Study Area

The Sardinia Region, with a surface area of 24,090 km^2, is one of the largest islands in Italy (third in Italy), with a population of 1,578,146 inhabitants (2023) and a population density value of 66 inhabitants/ km^2, among the lowest nationally. The progressive evolution of the administrative geography [14] has led to the current configuration which consists of four provinces (Nuoro, Oristano, Sassari, and South Sardinia), a metropolitan city (Metropolitan city of Cagliari) and 377 municipalities.

The Sardinia Region has a strong tourist vocation, characterized by a marine-seaside tourism model, which reaches its peaks in the summer season, mainly affecting the coastal areas, where 90% of the offer of regional beds is concentrated and the '80% of tourist flows [15]. Seasonal tourism prevails over other forms of tourism. With the Regional Strategic Plan for Tourism (2023–2025) [16], the Region intends to encourage

the digital transition to implement the monitoring activity and enhance the territorial capital in order to diversify the tourist offer [17, 18].

The transport systems in Sardinia consist of [19, 33]: around 9000 km of road network (State and Provincial Roads); 427 km of Italian railway network (RFI) [34], in addition to which the railway network managed by the Sardinian Regional Transport Company (ARST) and the tourist railway networks (Trenino Verde) should be considered; eight ports administered by the Port System Authority of the Sea of Sardinia (Cagliari, Olbia, Porto Torres, Golfo Aranci, Portovesme, Oristano, Santa Teresa di Gallura, Arbatax); three international airports (Cagliari, Olbia, Alghero) which are fundamental for guaranteeing movements (cargo and passenger movements) to and from the Sardinia region (Fig. 1).

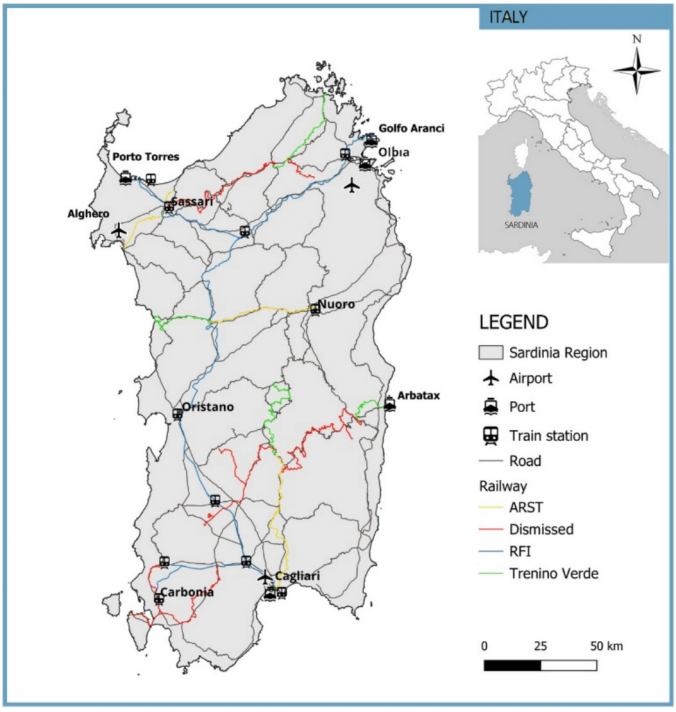

Fig. 1. The regional transport systems in Sardinia (Italy).

However, a substantial gap in the infrastructure system emerges. The poor road and rail accessibility increases the condition of marginality, especially in the internal areas, some of which lack rail connections with the main airports and ports of Sardinia [20]. On the other hand, the private rental and rental with driver (NCC) sectors are growing, helping to rebalance the transport offer in areas with weak demand, guaranteeing connections with the most important centers on the island.

2.2 Data

In line with studies focused on tourist flows and destination management [21–23], the data collected to analyze the spatial distribution of tourist flows in an island context are based on (Table 1):

– n. arrivals and departures (daily, monthly, and annual), from ports and airports
– n. arrivals and presences (monthly and annual), on a municipal basis

Table 1. Dataset to support geospatial analysis of tourism flows in Italy and in the insular case study.

Gateway and Territory	Data	Time	Source (Tourism and Mobility Observatories)	
			Italy	Insular case study
Port	Total arrivals and departures	Year-Month-Day	Italian Ports Association (Assoporti) [26]	Sardinia Region_Sardinia Mobility [24]
Airport	Total arrivals and departures	Year-Month-Day	Italian Airport Association (Assaeroporti) [10]	Sardinia Region_Sardinia Mobility [24]
Tourism destination	Total arrivals and presences (municipality, province, region)	Year-Month	Eurostat [3]	Sardinia Region_Sardinia Tourism [25]
			Banca d'Italia [7]	
			Nomisma [27]	
			USC [11]	

As part of this study, the main open-source data relating to tourist flows in Italy and Sardinia were collected and analyzed. With reference to the latter, the data for the three-year period 2019–2022 can be downloaded in csv format from the main websites of the Sardinia Region:

– arrivals and departures at the island's ports and airports (updated daily) [24].
– arrivals and presences in the municipalities of the island, which inform about how many people arrive each month, where they come from and how long they stay (updated annually) [25].

2.3 Methodology

The proposed methodological approach develops geospatial analysis to evaluate the spatial distribution and patterns of tourism flow in the insular Sardinia Region.

The spatialization of data, i.e. the process of representing and organizing data in relation to physical space, allows you to collect, visualize, analyze, and interpret spatial or geographical data according to their position on the earth's surface.

Geospatial analyzes highlight specific patterns and relationships and correlations between data, producing significant information, also to support sustainable regional planning [28, 29].

The method proposes a double geospatial analysis to evaluate respectively the density of the observed phenomenon (Kernel Density Estimation - KDE) and its spatial autocorrelation (Local Indicator Spatial Autocorrelation - LISA) [30].

The Kernel Density Estimation (KDE) technique is used to analyze the concentration or dispersion of elements in a specific geographic space. The KDE transforms punctual events into a continuous density function distributed in the region of interest, allowing the phenomenon to be represented through a three-dimensional surface that expresses the variation in the density of punctual events in the study area. In fact, KDE uses a three-dimensional kernel function to weight events within a radius of influence (radius parameter or threshold) [31].

The choice of the radius value depends on the nature of the data, the objective of the analysis and the characteristics of the phenomenon studied [5]. A low radius value produces local peaks in the density distribution. On the contrary, a high radius value produces a dilution effect on the observed phenomenon.

Then, the KDE technique identifies the spatial distribution of the studied phenomenon, highlighting regions of high density (clusters) or regions of low density (voids). At the same time, spatial autocorrelation techniques are used to analyze the spatial distribution of objects (whether they are arranged randomly, aggregated, or dispersed in space) and to evaluate the degree of influence and relationship with neighboring elements, i.e. spatial dependence between geographical entities, through various indicators [30].

Moran and Geary's global spatial autocorrelation indicators provide information on the autocorrelation itself, while the localization of high autocorrelation values is provided by local indicators [32], through which the possible presence of clusters or dispersion is highlighted. An example is the Local Indicators of Spatial Association (LISA) index, which evaluates whether a given area of a space has a similar distribution of a variable compared to surrounding areas. LISA is considered as a local Moran indicator, which is directly proportional to the sum of all local indices. The indicator allows, for each location, to evaluate the similarity between each observation and the surrounding elements.

Five cases can occur, in which the different places are characterized by: high values of the phenomenon and high levels of similarity with the neighborhood (high-high); low values of the phenomenon and low levels of similarity with the neighborhood (low-low); high values of the phenomenon and low levels of similarity with the neighborhood (high-low); low values of the phenomenon and high levels of similarity with the neighborhood (low-high); absence of significant autocorrelation.

In this study, the two geospatial analysis techniques are used to evaluate the possible correspondences between the spatial density of the observed phenomenon and its spatial autocorrelation.

3 Results

The study applies the methodological approach in the Sardinia Region, selected as the first study area.

The geospatial analysis of the data relating to arrivals and departures in the ports and airports of the island and the presences recorded in the various municipalities in the period considered (2019–2022), shows a trend of tourist movements to and from the island in constant growth, with the exception of two years (2020 and 2021), when, due to the Covid-19 pandemic, there was a decline in both arrivals and departures compared to previous years.

As regards the data referring to arrivals and departures, in ports and airports, a very similar situation emerges in the years 2019 and 2022 (Fig. 2): the airports of Cagliari and Olbia record a higher number of arrivals and departures than at Alghero airport. Among the ports, the most active one is certainly that of Olbia, recording 1,444,528 arrivals and 1,464,778 departures in 2022.

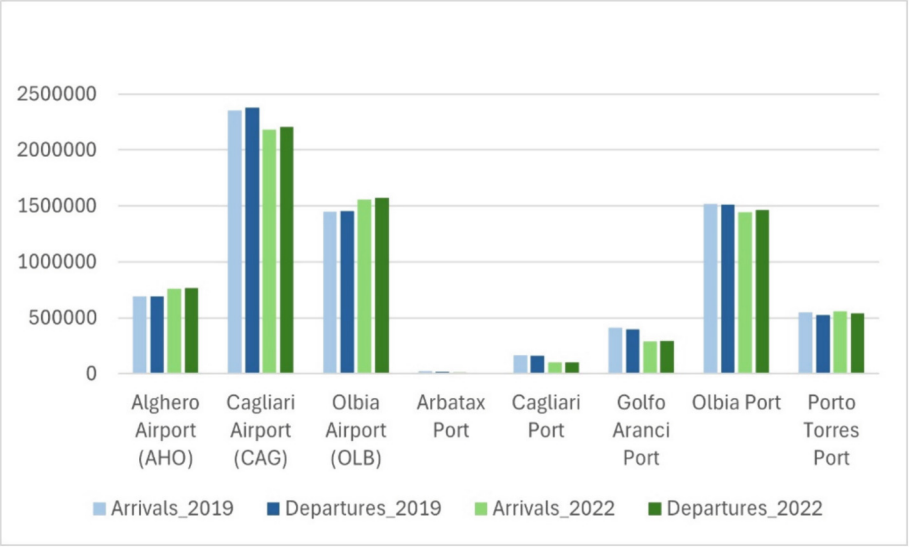

Fig. 2. Arrivals and departures of passengers in the main ports and airports of Sardinia, in the years 2019 and 2022.

The KDE and LISA relating to the number of arrivals and presences recorded in the municipalities of the island highlight the main tourist destinations in relation to the duration of stays (number of days).

The objective of analyzing tourist flows through the KDE technique, with a focus on the municipal scale, required the calculation of the average distance between the centroids of the municipalities of the island to define the size of the radius and, subsequently, the relationship between radius and cell. In the Sardinia Region, this distance is approximately 5 km.

Adopting a radius to cell ratio of 10:1, the KDE was performed by setting a radius of 5 km and the cell of 500 × 500 m. The values chosen for the radius and for the cell allow a representation of the phenomenon excluding the following opposite scenarios [31]: on the one hand, the definition of bandwidth values lower than 500 m, with a spiky representations of the phenomenon, which may provide not much more information on the distribution than the simple observation of the point distribution; on the other hand, the definition of bandwidth values higher than 500 m, with may produce an excessive dilution of the spatial pattern.

The geospatial analysis of presences in the months of August and December produced by KDE does not reveal significant differences between 2019 and 2022 (Fig. 3; Fig. 4). The little difference between the pre- and post-pandemic periods testifies to the rapid recovery of the sector.

Rather, a substantial difference emerges between the winter and summer months, underlining the strong seasonal nature of Sardinia tourism. Furthermore, the presence of regions of high density (clusters) or regions of low density (voids) emerges: the coastal areas are much busier than the more internal areas of the island, with a greater distribution of arrivals near the ports and airports.

Below are the results of the KDE (Fig. 3; Fig. 4) and the LISA method (Fig. 5; Fig. 6) in reference to the data on presences in the months of August (peak month of the summer season) and December, for the years 2019 and 2022.

The results of the KDE analysis confirm several characteristics of the consolidated tourism model in the Sardinia region:

i) a substantial difference in the number of arrivals, departures and presences between the summer and winter seasons, which emphasizes the seasonal nature of Sardinian tourism.
ii) the concentration of arrivals and presences in the coastal areas, which are much more popular than the inland areas (coastal over tourism).
iii) the presence of three main clusters in the month of August, which correspond to the main tourist destinations on the island.
iv) the low attractiveness of inland areas and rural areas, even though they are a privileged destination for other forms of tourism, especially those attributable to slow tourism.

In reference to point iii), the presence of clusters in direct proximity to the urban/port-airport systems of the island (high concentration of tourist movements near the airports), is linked to the significant gaps in the internal connection network, in particular of those to and from the airports/ports, with a consequent increase in the peripherality of some parts of the territory.

The LISA maps for arrivals and presences in the months of August and December for the years 2019 and 2022 (Fig. 5; Fig. 6) reveal a low-low autocorrelation for the internal areas, therefore characterized by a low level of the phenomenon and low levels of similarity. At the same time, the high-high clusters in the main tourist destinations of the island coincide with the results of the KDE, thus confirming the methodological approach.

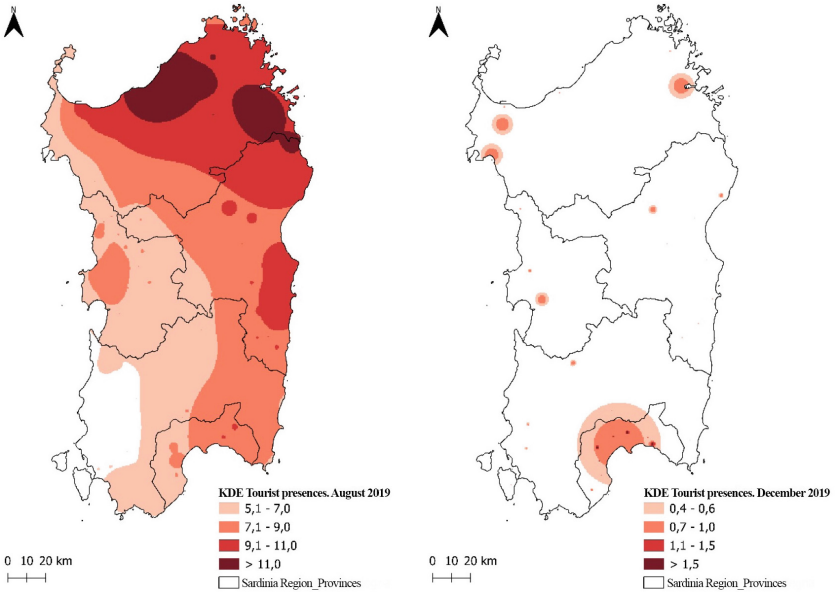

Fig. 3. KDE. Comparison between the spatial distribution of the tourist presences in the Sardinia Region (August 2019; December 2019). R = 5 km, cell of 500 × 500 m.

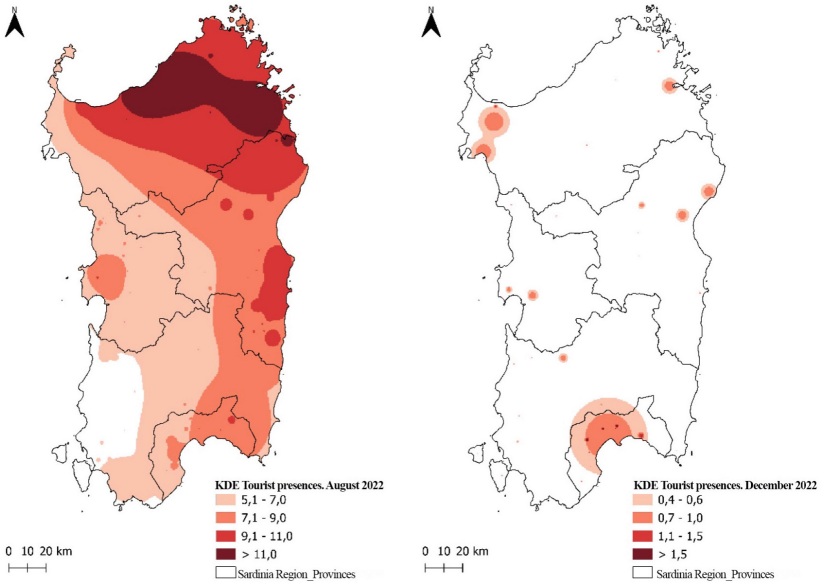

Fig. 4. KDE. Comparison between the spatial distribution of the tourist presences in the Sardinia Region (August 2022; December 2022). R = 5 km, cell of 500 × 500 m.

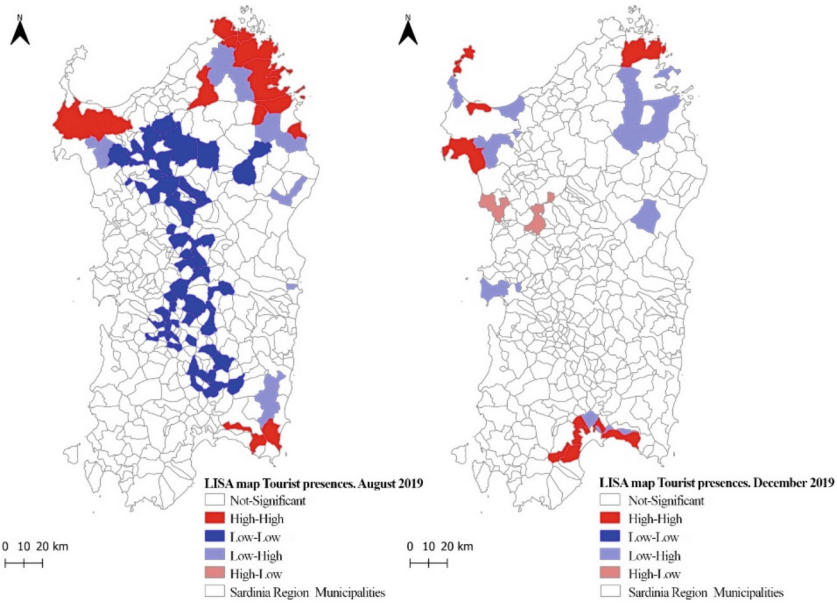

Fig. 5. LISA maps from GeoDa application. Comparison between the spatial distribution of the tourist presences in the Sardinia Region (August 2019; December 2019).

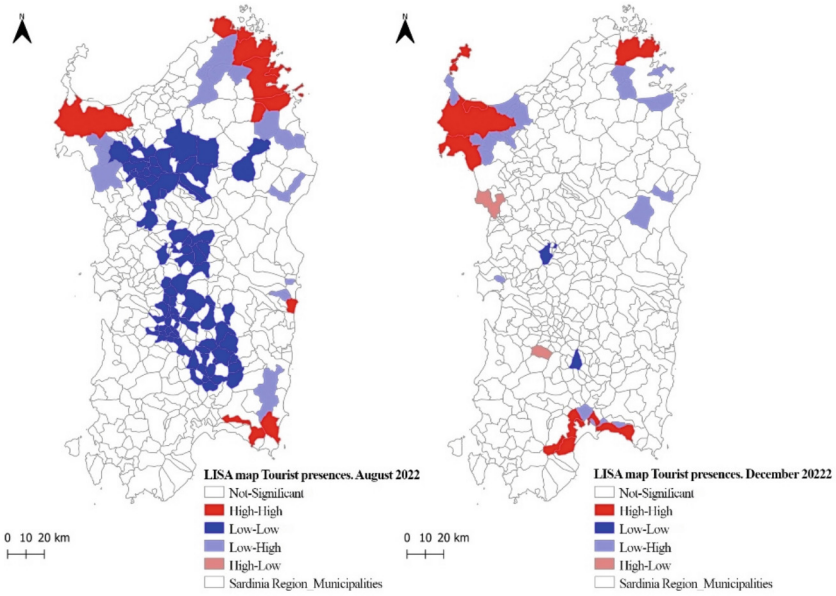

Fig. 6. LISA maps from GeoDa application. Comparison between the spatial distribution of the tourist presences in the Sardinia Region (August 2022; December 2022).

4 Conclusions

The study proposed a methodological approach based on geospatial analysis techniques (KDE and LISA) to analyze the density and spatial autocorrelation of tourist flows in the Sardinia Region in the period 2019–2022.

The geospatial analysis revealed a constant growth trend in arrivals on the island, except in the years 2020 and 2021, in which, due to the Covid-19 pandemic and the consequent limitation of mobility, there was a decline in numbers. The research therefore focused mainly on the years 2019 and 2022 to evaluate if and how the health crisis has influenced tourism development in the Sardinia region. The results of the geospatial analyzes do not reveal differences between the pre-pandemic and post-pandemic periods, which testify to a rapid recovery of the sector. The seasonal nature of Sardinian tourism is confirmed, with significant peaks in the summer months (over tourism), and a distribution of arrivals mostly concentrated along the coasts. At the same time, it was possible to record positive changes in attendance in some internal areas, albeit relatively limited.

Therefore, encouraging the overcoming seasonality and redistribution of tourist movements across the entire regional territory becomes an objective to be pursued also in light of the progressive establishment of slow tourism as an integral part of Sardinia's tourist offer, mainly involving inner and rural areas.

Furthermore, geospatial analyzes show a concentration of the number of presences in an area of approximately one hour from the main ports and airports due to the higher levels of connectivity compared to the rest of the territory, characterized by weak supply and demand for transport. This condition stresses the disadvantages of being an insular context. In this sense, improving transport systems between urban hubs and the main gateways, to ensure effective and sustainable mobility to support tourists and, above all, the resident population, allows the implementation of the main policies developed within the framework of the principle of insularity, recently inserted into the Italian Constitution (art. 119). Furthermore, the presence of clusters of presences in the main tourist destinations of the island recall the need to develop shared policies between the municipalities belonging to the same cluster.

The results obtained support the e.INS project aimed at structuring a sustainable transport offer serving the population and city users, which adequately considers the connections between the road and railway networks and transport hubs in the regional territory, with particular attention to airports and ports, in line with the new perspective of Mobility as a Service (MaaS) and in coherence with the National Airport Plan (2022).

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The Challenges of Demographic Transition. Network Analysis to Assess Spatial Accessibility to the Emergency Health System

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Abstract. The demography in Europe is in a stagnant phase, correlated to low fertility and mortality rates, typical of a modern and economically advanced society. Italy is one of the European countries with the oldest population, recording the highest median age of the population in 2022 (48 years). The "silver economy", i.e. the consumer economy that characterizes the population of 50–65-year-olds, up to the over 65s, needs specific services. In this sense, progressive demographic changes also require a renewed public governance, especially in terms of spatial accessibility of the emergency health system. In this framework, the study applies Network Analysis Technique to evaluate the spatial distribution of the population – with a particular focus on the over 65 population - and the relative accessibility to the network of the health emergency services on a regional scale. The insular context of the Sardinia Region (Italy) represents an interesting case study due to the significant silver population and the related multipolar spatial distribution in the 377 municipalities, affected by peripherality and marginality issues. The manuscript, which is part of the e.INS project, provides useful information and approaches to support the construction of a regional MaaS solution to improve the accessibility to the emergency health system.

Keywords: Demographic Changes · Health System · Spatial Accessibility

1 Introduction

Population aging is the most pervasive and dominant global demographic trend of our time [1]. According to the latest World Social Report [2], people aged 65 or older worldwide is expected to more than double, from 761 million in 2021 to 1.6 billion in 2050. The EU population is also aging: the number of people aged 80 years and older has increased in all Member States in 2022 [3]. Half of the EU's population is older than 44.4 years. Italy is one of the countries with the oldest population, recording the highest median age of the population in 2022 (48 years).

According to these trends, the emergence of an inverted population pyramid will be a real challenge for human development in the future. Changing demographics will also shape urban governance, especially in terms of the provision of both social services of

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general interest and specialized urban services. As a matter of fact, the "silver economy", i.e. the consumer economy that characterizes the population of 50–65-year-olds, up to the over 65s, requires a specific system of services [4, 5]. Among these, within the strategic mission of a renewed spatial planning [6], health and welfare services represent primary services to be guaranteed, also in terms of adequate spatial accessibility [7]. This is a challenge, especially in Italy, where the issue of the peripherality of internal areas is of great importance in the scientific and political debate [8].

In this framework, the paper proposes a methodological approach to evaluate the spatial accessibility to the hospital emergency network (HEN) in the Autonomous Region of Sardinia (ARS) (Italy), selected as a case study. The study uses Network Analysis (NA) techniques to analyze the spatial distribution of the population (2023), especially of the population ages 65 and above, thus detecting the level of accessibility to the HEN by public and private means of transport.

The manuscript is part of the e.INS project, which proposes forms of sustainable mobility in the regional territory of Sardinia, also for health purposes, in line with the concept of Mobility as a Service (MaaS) [9].

The manuscript is organized as follows: Sect. 2 - Literature review - provides a description of the demographic transition model, at the international and national scale (Sect. 2.1), and introduce the main issues concerning the role of spatial accessibility in urban and regional planning in Italy (Sect. 2.2); Sect. 3 - Materials, data and methods - provides a description of the study area (Sect. 3.1), the methodology (Sect. 3.2) and the dataset (Sect. 3.3) to assess the spatial distribution of the population and, therefore, the level of accessibility to HEN in the ARS; Sect. 4 and Sect. 5 discusses respectively the main results of the study and the next steps.

2 Literature Review

2.1 Stages of the Demographic Transition

The demographic transition has long been the subject of research both in the academic field and within other public and private institutions, in support of national and/or international governance. The demographic transition represents the process of change in the demographic structure of the population, in relation to the economic, social, and cultural transformations of society [10–12], from the changes observed from the pre-industrial phase to the current fourth revolution (industry 4.0) [13–15]. The demographic transition is also closely related to health, well-being, and education policies [16, 17] and can be represented in the following five stages (Fig. 1):

Stage 1 - Preindustrial: In this phase, both birth and death rates are high, resulting in slow population growth. The high birth rate is compensated by the equally high mortality, mainly due to diseases and wars, poor hygiene, and poor nutrition. This phase is typical of significantly backward socioeconomic contexts.

Stage 2 - initial transition: There is a reduction in the mortality rate thanks to improvements in living conditions, as a result of healthcare and a balanced diet. However, the birth rate remains high, leading to rapid population growth.

Stage 3 - advanced transition: The birth rate begins to decline, following the decline in mortality. This change is often attributed to economic factors, access to education, particularly for women, and birth control. Population growth slows.

Stage 4 - post-industrial: Both birth and death rates are low, stabilizing at a population growth rate close to zero or even negative. This phase is characterized by an elderly population, with challenges linked to the support of the elderly by the working age population, which is progressively decreasing.

Stage 5 - post-transitional: Fertility rates could fall below population replacement levels, leading to a long-term decline in population if not offset by net migration. This phase is characterized by demographic challenges, such as an aging population and a declining workforce.

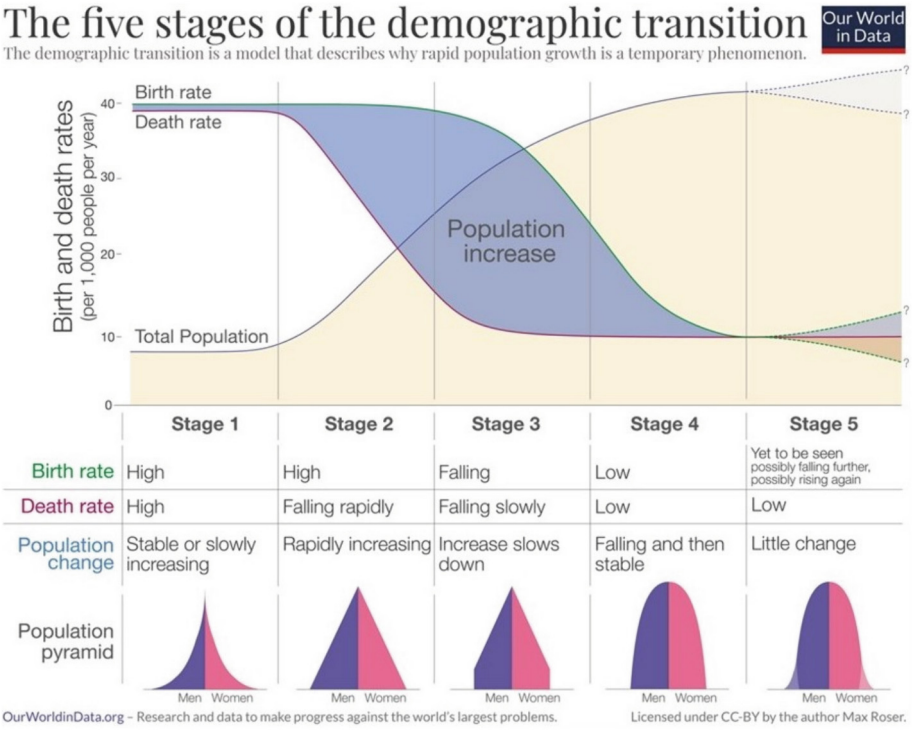

Fig. 1. Stages of the Demographic Transition [12].

As into the European international context, Italy moves towards stage 5. As a matter of fact, the decrease in the birth rate, associated with a progressive aging of the population, has long been a constant, generating new challenges for governance, also in terms of spatial accessibility of the emergency health system, in response to the spatial distribution of the over 65 population [18, 19].

2.2 Inner Areas and Accessibility in Italy

The importance of providing an adequate spatial accessibility of the emergency health system represents a real challenge, especially in Italy, where the issue of the peripherality of internal areas is addressed in the scientific debate and in the political agenda [20].

The National Strategy for "Inner Areas" (SNAI) (2014) [21–23], a national development and cohesion policy, defines a polycentric structure of Italy, characterized by a system of urban centers and peri-urban areas, and by a series of medium and small municipalities, characterized by a different level of accessibility, calculated in terms of travel time necessary to reach the nearest urban center [24]. More precisely, urban center and peri urban areas correspond to those municipalities or aggregations of municipalities where the offer of primary services such as secondary schools, hospitals with a Department of Emergency and Acceptance (DEA) level I and platinum, gold or silver train stations is concentrated and accessible within 20 min ($t = 20$ min).

Instead, the municipalities falling within the so-called "internal areas" are identified based on the level of accessibility to the three citizenship rights mentioned above (mobility, education, and health): intermediate areas ($20 < t < 40$ min); peripheral areas ($40 < t < 75$ min); ultra peripheral areas ($t > 75$ min). The proposed classification reflects the degree of spatial peripherality.

The marginal territories, characterized by important geographical or demographic disadvantages, distant from the main urban centers and services, cover a total of 60% of the country's total area, 52% of the Municipalities and 22% of the population [25].

The ISTAT report (2023) on the accessibility of Italian municipalities to infrastructure nodes relating to four types of transport networks (road, railway, maritime and air) [26], states that:

- approximately 53% of the municipalities and 75% of the population are half an hour from the nearest train station.
- approximately 38.9% of municipalities and 60% of residents can access the motorway network within 15 min.
- approximately 14% of municipalities and 35.8% of the population can reach the airport within 30 min.
- only 9.4% of the population (85 Municipalities) reaches a passenger port within 15 min.

Another ISTAT report (2024) on the accessibility of Italian municipalities to the mail public services (pharmacies, emergency rooms, police, municipal offices, food shops and markets, supermarkets) [27], reveals that 50.8% of families have difficulty reaching the emergency room, an increase of 1.6 percentage points compared to 2022. The highest percentages are found in the South (59.5%, approximately seven percentage points more than the national average), followed by the Islands and the Center (52.7% and 52.4% respectively). The value exceeds the national average in some regions (11). The highest percentages are recorded in Campania (63.5%), followed by Calabria (62.5%), Liguria (58%) and Puglia (57%). The difficulty of Italian families is greatly influenced by the spatial distance to the emergency rooms. As a matter of fact, in the Metropolitan areas, the difficulty is equal to 43.8%, while in the small municipalities (under 2,000 inhabitants) it rises to 68.6%, thus increasing the perception of marginality and peripherality.

In this sense, investments in territorial resources and accessibility to counteract the marginalization and demographic decline of inner areas are at the core of the SNAI. Spatial accessibility represents a precondition for developing policy and territorial planning strategies: the level of accessibility to an infrastructure or a primary service affects the quality of life and the competitiveness and productivity of businesses.

3 Materials, Data, and Methods

3.1 Study Area

The Autonomous Region of Sardinia (ARS) is an Italian island region with 1,578,146 inhabitants (2023). It extends for 24,090 km2, representing the second largest island in the Mediterranean, after Sicily, and the first Italian region for coastal development (1,897 km). The administrative division consists of provinces - Nuoro (NU), Oristano (OR), Sassari (SS), South Sardinia (SU) -, a metropolitan city - Metropolitan City of Cagliari (MCC) - and 377 municipalities.

Like Italy, the Sardinia region is affected by the phenomenon of demographic decline. In the last 10 years (2013–2023) it lost 85,713 inhabitants. According to ISTAT forecasts, the Italian population will decrease from 59 million on 1 January 2022 to 58.1 million in 2030, and again from 54.4 million in 2050 to 45.8 million in 2080 [28].

The decrease will be even more marked in Sardinia, where in 2022 the lowest level of fertility in Italy and the minimum value of children per woman was recorded [29]. The Sardinian population has an age structure that is significantly older than the Italian average [30]. In 2021 the regional average age is 48.1 years, higher than the national average of 46.2 years.

Within this framework, one of the most complex challenges is the optimization of the provision of the health system to respond to the demand for assistance, in particular from the older segments of the population.

However, guaranteeing adequate levels of healthcare represents an arduous challenge, especially as regards spatial accessibility to the HEN, threatened by significant mobility gaps, in extra and intra-territorial continuity. As a matter of fact, the primordial condition of disadvantage in the extra territorial continuity (movements to and from Sardinia) is worsened by a weak offer of transport services and infrastructures (especially with reference to roads and railways) [31]. Travel times for movements within the island, among the highest in Italy, further aggravate the condition of insularity [32] and requires a renewed public governance capable of addressing the challenges of the demographic transition [33], guaranteeing an age-friendly region [34].

3.2 Method

Several studies analyze the relationship between the quality of healthcare and the main demographic indicators (life expectancy at birth, longevity, mortality rate, etc.) [35–37], proposing methods to measure the potential travel times needed by the population to reach health services [38, 39].

Within this framework, the authors propose a methodological approach to evaluate the spatial accessibility to the hospital emergency network (HEN). The study uses

Network Analysis (NA) techniques to analyze the spatial distribution of the population, especially the population ages 65 and above, thus detecting the level of accessibility to the HEN by public and private means of transport. Spatial network analysis is used to analyze the spatial relationships between nodes in a geographic network [40]. Processing network analysis tools in QGIS support the calculation of:

- the shortest and/or fastest path between two points of a network (shortest path /layer to point; shortest path/point to layer; shortest path/point to point).
- the areas reachable from a specific point, chosen manually or from a point layer, based on a specific distance or time (service area/from point; service area/from layer).

More precisely, starting from a specific spatial typology, in which the geographical position of the nodes (points) and connections (arcs) within the network is identified, the network analysis allows the evaluation of spatial accessibility, i.e. the degree of ease with which a node can be reached from other points of the network, considering spatial characteristics. In this sense, processing network analysis tools also support the definition of isochrones, i.e. maps that show the areas that can be reached within a given time from a starting point, considering variables such as travel speed and the road network, or the speed of public transport available. Isochrones can be calculated for pedestrians, cars, bicycles, or public transport. Isochrones can be used to evaluate the coverage of services and the level of accessibility, providing useful support to several disciplines, including urban planning and transport planning.

GIS (Geographic Information Systems) software and online mapping applications offer tools to generate isochrones [41]. The Travel Time application plugin [42], for example, adds a toolbar and processing algorithms allowing to query the TravelTime API directly from QGIS. The TravelTime API allows to obtain polygons based on travel time using different transport modes. TravelTime public transport model considers every possible route based on public transport timetables and data gathered from public transport agencies. Data comes from a continuous collection of public transport timetable data (GTFS data or timetables in other formats), incorporated into the TravelTime public transport model, and updated at least every two weeks. Several combinations of public transport methods are included, covering bus, coach, train (overground train, underground train), and tram. Walking is also included, to allow for moving between stops/stations etc.

3.3 Data

Data collected to assess the spatial accessibility of the Sardinian population, in particular the elderly (> 65 years), to the nodes of the HEN, by both private and public transport, are as follows (Table 1):

- census population [43], which provides information on the main characteristics of the resident population (sex, age, education, occupation, marital status, families), in reference to each census section.
- administrative boundaries (municipalities, provinces, metropolitan city) [44].
- nodes of the HEN [45], i.e. the services considered fundamental to evaluate the level of marginality and peripherality of the municipalities, in line with the SNAI

objectives. The 22 nodes located throughout the regional territory (data updated as of 30 December 2021) [46] are as follow: n. 11 emergency rooms (ER); n. 8 DEA Level I, located in the four provinces and in the Metropolitan City of Cagliari; n. 3 DEA Level 2, located in the Province of Sassari and in the Metropolitan City of Cagliari.
– Road network [47], fundamental for defining the isochrones and, therefore, calculating the population that can reach the nearest node of the HEN in a given time (20 min), through private or public transport.

Table 1. Dataset to support NA in the ARS.

Data	Source	File extension	Date
Census population	ISTAT [43]	xlsx, shp	2021
Administrative boundaries	ISTAT [44]	shp	2023
Nodes of the HEN	Ministry of Health [46]	xlsx, shp	2021
Road network	ARS_Geotopographic Database [47]	shp	2022

4 Results

In this study, the NA techniques of the QGIS software are used to define 20-min isochrones from the nodes of the Sardinian HEN, in order to evaluate the accessibility of the population, especially the over 65 population, through public and private transport modes. In particular, the Travel time application is used to evaluate accessibility by Local Public Transport (LPT). The results of the NA techniques used to evaluate the accessibility to the HEN nodes through private means of transport are presented below, considering a travel speed of 50 km/h (Fig. 2). Figure 2 also shows the TrivelTime 20-min isochrones by LPT, with reference to the 3 DEA Level I located in the cities of Olbia, Nuoro and Cagliari.

NA techniques reveal that 66.14% of the Sardinian population lives in urban centers equipped with a HEN node and in peri-urban areas (which reach the urban center in 20 min), while the rest live in inner areas. Moreover, 35.05% of the elderly Sardinian population live in inner areas.

In the MCC, the resident population is equal to 422,499 inhabitants, of which 102,936 are elderly (24.36%). The MCC records the highest levels of accessibility to the HEN nodes, exceeding the regional average by several percentage points: 88.20% of the population lives in urban centers and surrounding areas. The most populous province, that of Sassari (SS), with 476,516 inhabitants, of which 24.55% are over 65 years old, records levels of accessibility to the HEN nodes closer to the regional average: 67.22% of the population lives in urban centers, 32.79& in internal areas. The lowest levels of accessibility are recorded in the following provinces: Nuoro (NU), Oristano (OR) and South Sardinia (SU). More precisely, in the province of Nuoro, almost 64% of the total population and over 63% of the elderly population live in inland areas. The same provinces also record the lowest life expectancy values compared to the regional and national average.

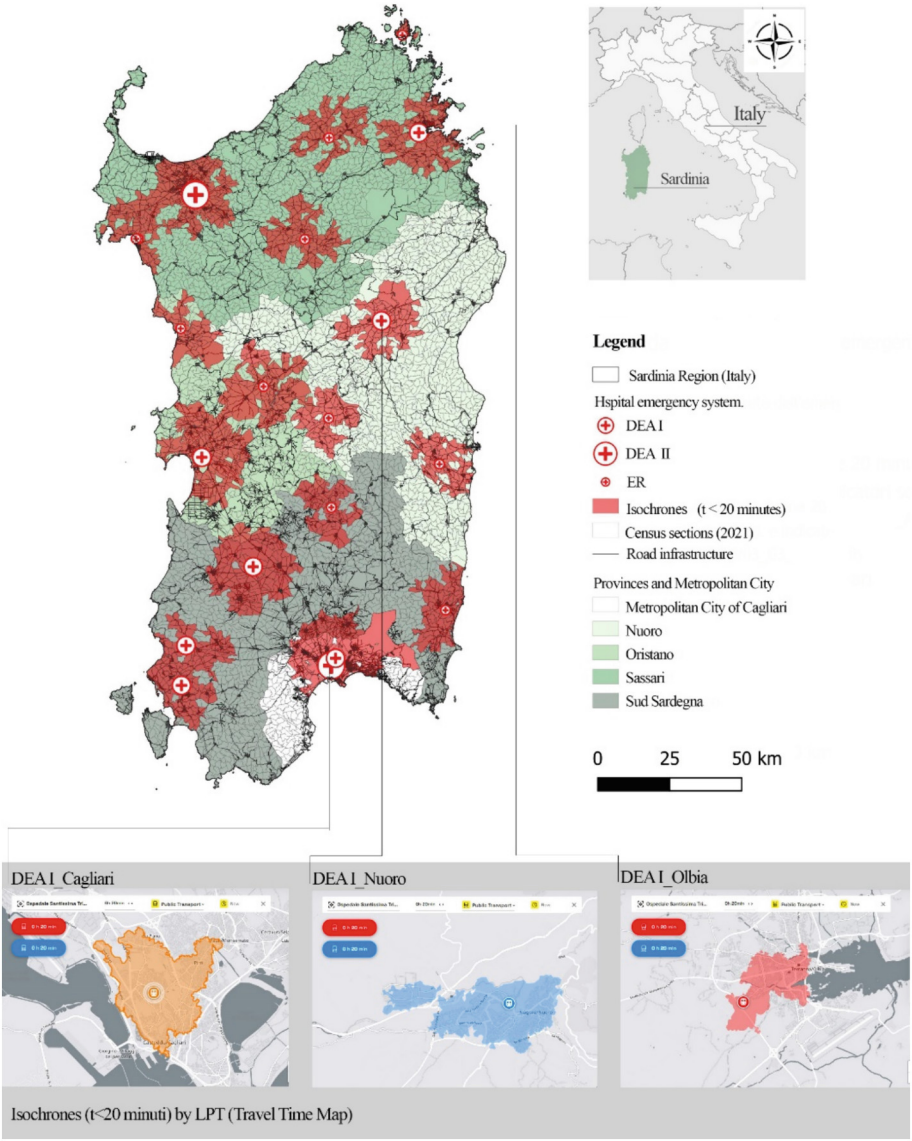

Fig. 2. At the top, the isochrones (20 min from each node of the HEN) by private transport. Below, the isochrones (20 min from the DEA I of Cagliari, Nuoro and Olbia) by LPT (Source: Travel Time Map). Author: Mara Ladu

According to the Provincial BES indicators [48], in 2022, life expectancy at birth in Sardinia (82.5 years) is slightly higher than the national value. The province of Cagliari is the one with the highest value at a regional level (83.8 years), higher than the national

average Fig. (82.4 years), while that of Nuoro records the lowest value (81.7 years), i.e. almost one year less than Sardinia and Italy. Low values compared to the regional and national average are also recorded in the provinces of Oristano and South Sardinia (Table 2). This explains the close relationship between health policies, well-being, and demographic transition.

Table 2. Life expectancy at birth. Data on provincial, regional, and national level.

Indicator	Territorial scale	Cagliari	Nuoro	Oristano	Sassari	South Sardinia
Life expectancy at birth	Province	**83,8**	**81,7**	**82,0**	**82,5**	**82,2**
	Region (Sardinia)	82,5	82,5	82,5	82,5	82,5
	Country (Italy)	82,4	82,4	82,4	82,4	82,4

5 Conclusions

The authors proposed a methodological approach that applies the Network Analysis (NA) technique to analyze the spatial distribution of the population, especially of the population ages 65 and above, and evaluate the accessibility to the node of the Health Emergency Network (HEN) in the Autonomous Region of Sardinia (ARS).

The results reveal that approximately 60% of the Sardinian population is concentrated in urban centers equipped with a node of the HEN and in peri-urban areas, as defined by the SNAI. The remaining population, of which 35% is over 65, lives in the inner areas: intermediate areas; peripheral areas; ultra-peripheral areas.

The geographical spatialization of the population, classified by age target, deserves particular attention by virtue of the demographic transition. As a matter of fact, the recent forecasts developed by ISTAT on demographic dynamics (2023–2031) [49] reveal that the population ages 65 and above will be concentrated mainly in the municipalities that are part of the I and II belt of metropolitan cities.

The method based on network analysis can be applied in other regional contexts, also to develop comparative studies to support urban and transport planning, as well as policies in those areas where low levels of accessibility to the HEN have been recorded, considering the opportunities provided by the MaaS solutions. In this sense, the study is part of the research activity developed to create the multilevel geodatabase of the e.INS project, which intends to propose forms of sustainable mobility in the extra- and intra-territorial continuity) [50] in a space of proximity to guarantee the right to health.

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A Scoping Review of the Barriers and Prerequisites for MaaS Implementation in Low-Demand Contexts

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Abstract. MaaS, the acronym for Mobility as a Service, denotes the emerging mobility paradigm whose widespread development involves many different countries. It is a user-oriented travel planning solution that combines multiple mobility systems from both public and private operators into one digital platform. The platform supports the user at all stages of the journey: planning, booking, and payment, and promotes the integration of different transport systems according to principles of efficiency and sustainability. To date, MaaS deployments have mainly been in densely populated urban areas, where higher travel demand, infrastructure connectivity, and service provision make this solution more cost and performance-efficient. In regions characterised by low population density, inadequate infrastructure and network coverage, and poor transport services, MaaS solutions are much less likely to be adopted. Despite low passenger numbers and poor financial performance, the highly personalised and adaptable nature of the service, facilitated by the support of the latest technologies, suggests such a formula for improving the mobility of specific groups of users (inhabitants of low-density areas, people with special needs such as the disabled and the elderly). With this assumption, the paper aims to investigate the feasibility of MaaS systems as a solution for passenger transport in low-demand areas, starting with a scoping review of the literature focusing on the prerequisites and limitations of its practical implementation. The selected studies have shown the complexity of the issue and the need to adopt a multi-level perspective due to the very diverse and variable nature of the factors involved. However, such an approach is still rarely used in favour of sectoral studies focusing on specific technical aspects, mainly related to operational performance, efficiency, and economic viability. Much less attention is paid to the social impact of MaaS solutions, i.e. their potential to contribute to territorial rebalancing and the inclusion of vulnerable groups. Further research is needed to develop a practical model that can be used in low-demand situations and that combines cost-effectiveness with environmental, social, and governance principles.

Keywords: Mobility as a Service · Scoping Review · low-demand contexts

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1 Introduction

The research aims to define favourable conditions for the implementation of Mobility as a Service (MaaS) in low-demand contexts. MaaS refers to the emerging mobility paradigm that is being widely developed across several countries. It is a user-oriented travel organisation solution that is focused on meeting the needs of users. It combines a telematic platform with multiple transport systems, including both public and private operators, all within the same environment. The system provides combined transport solutions for users, assisting them in planning, booking, and paying for the services required to travel between the place of origin and destination [1, 2].

This solution is mostly feasible in highly populated urban contexts because of its infrastructure, cost-effectiveness and performance efficiency. In contrast, MaaS solutions are less widely accepted in marginal realities characterised by lower demand levels and weaknesses in infrastructure and service supply. However, the highly customised and adaptable nature of the service to a variety of needs suggests this formula for improving mobility in marginal contexts. Starting from these assumptions, this paper aims to investigate the possibility of implementing a MaaS system even in structurally weak contexts. It will begin by exploring the needs, challenges, and barriers to implementation.

The increasing need for daily travel for a variety of reasons has compelled the average user to consider the costs of getting to a destination first when selecting a mode of transport. Therefore, the possibility of choosing alternative solutions has become critical. However, the mobility sector has recently suffered a setback due to the Covid-19 pandemic. The implementation of social distancing measures has resulted in a decrease in demand for transport [3] and a decline in the use of collective modes for longer distances.

The Covid pandemic and the increasing use of ICTs have also highlighted the usefulness of mobility planning information and support services for both end-users and transport managers, as well as the need to ensure equality of access to basic services for all urban and suburban citizens.

Therefore, an in-depth review of the existing studies on Mobility as a Service (MaaS) solutions in low-demand situations was conducted. To achieve this goal, the paper is organised as follows: Section 2 illustrates the methodology adopted, Sect. 3 presents results, Sect. 4 reports the discussion of results and the Sect. 5 presents the conclusions.

2 Method

The selection and further analysis of scientific contributions were conducted using the method proposed by Arksey and O'Malley [4] and the most recent updates to the process proposed by Peters et al. in 2020 [5]. The methodological process was divided into five stages as shown in Fig. 1:



Fig. 1. Methodological process diagram

2.1 Research Question and Study Design

The definition of the research question is a central part of the methodological process. It guides the research strategy by specifying the topic, the scope of the investigation and the objectives that the study sets for itself [4].

The broader concept examined here is the implementation of MaaS solutions in low-demand contexts. We are interested in investigating the feasibility of such a model of mobility in these specific situations, focusing on the drivers and barriers to its implementation.

The following sub-questions helped to articulate better the main question:

1. What are the main drivers and barriers to MaaS implementation in low-demand contexts?
2. Is there evidence, success/failure experiences to take as case studies?
3. What conditions or structural features of contexts influence the feasibility of MaaS solutions in low-demand situations?
4. How can we measure and evaluate the maturity level of implementation contexts?
5. What planning strategies or policies have been introduced to make MaaS effective in low-demand areas?

These specific questions directly guided the definition of the inclusion criteria to be considered.

The purpose of the study is to summarise the available literature on this topic, by considering time, source, authors' fields of expertise and country, context of application, study designs and research methods, and study outcomes. In this way, the authors aim to provide an overview of the scientific debate on the topic, which may be useful for future research and, in particular, for informing planning practice.

2.2 Identification of Relevant Studies

It should be noted that the term MaaS has lately been integrated into the disciplinary lexicon, both in theory and practice. As a consequence, the search has been limited to scientific production in the last ten years including peer-reviewed studies, grey literature, and literature reviews.

The search strategy is based on the use of a set of keywords representative of the new mobility paradigm (seamless trips using multimodal transport options via a single digital interface) and of context intended as environments with low or seasonally variable transport demand (Table 1).

The concept of low mobility demand is generally associated with low population density contexts, such as rural areas. To broaden the range of contexts to consider in the analysis, the authors added "low demand area", "weak demand area", "inland area",

Table 1. Search settings.

Search themes	Keywords
Mobility	MaaS, Mobility as a Service, Demand Responsive Transport, Combined Mobility, Seamless Mobility Flexible Mobility, Share Mobility, On-demand transit, Inclusive Mobility, Paratransit
Context	Weak demand area(s), rural area(s), low demand area(s)

and "marginal context" among the keywords. The next stages of the process will define additional factors to characterise the contexts.

The selected keywords, combined with Boolean operators, resulted in the following string text used for the search: Mobility as a service OR Demand Responsive Transport OR Flexible Mobility OR On-demand transit OR Seamless Mobility OR Combined Mobility AND Inclusive Mobility OR Paratransit AND Weak demand area(s) OR Rural area(s) OR Low demand area(s).

The search for relevant contributions was conducted using two databases, Scopus and Web of Science, resulting in the identification of a total of 337 articles.

2.3 The Search Decision Process: Inclusion and Exclusion Criteria

The third step is to define the criteria for inclusion and exclusion, as outlined in Table 2, to screen the studies.

The two main eligibility criteria included the identification and discussion of conditions that hinder or facilitate the implementation of MaaS solutions, with a focus on marginal contexts. Excluded from consideration were articles that examined the use of MaaS solutions in densely populated contexts, such as cities, or dealt with paratransit systems (in urban contexts). Sector-specific contributions that had a technical focus, such as architecture or mathematical models of applications or service schemes, were also excluded. These were developed in disciplinary areas unrelated to and far removed from urban, spatial, and transport planning, which is the focus of this contribution. Even if their content is innovative and noteworthy, they do not provide knowledge relevant to the research question. For example, papers that discuss highly specialised aspects of ICT and require advanced knowledge and skills to read were excluded. Additionally, papers that discuss public transport during and after the Covid-19 pandemic were excluded.

The included contributions provide indications of several aspects, such as technical, functional, organisational, management, financial, and regulatory issues. These elements either facilitate or limit the implementation of MaaS solutions and flexible on-demand mobility services, such as Demand Responsive Transport or Flexible Transport Service in marginal contexts. Finally, of the studies that analysed the influence of individual factors on the uptake of MaaS solutions, only those that looked at the whole population, with no restrictions on specific groups (by age, gender, socio-economic characteristics, household composition, etc.), were included.

Table 2. Eligibility criteria

Inclusion criteria	Exclusion criteria
The consulted papers consist of peer-reviewed studies and grey literature They provide insights into MaaS systems, flexible mobility services and on-demand transportation such as DDRT in low demand or rural areas The papers address enablers and barriers to MaaS implementation	Articles that did not fit the research topic were removed based on title and abstract checks Articles with very specific technical focus requiring a high level of expertise in disciplinary areas far removed from urban and transport planning, were excluded

The authors completed the screening process in two steps, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart (Arksey & O'Malley, 2005). During the first step, the title and abstract were checked to gather a preliminary selection of articles that aligned with the research question. These contributions were then subjected to a second step of checking by reading the full texts.

Out of the 337 contributions, n = 12 were excluded as duplicates, while n = 259 were excluded for not meeting the eligibility criteria, as summarised in Table 2. Some of the papers discussed MaaS or DDRT systems but were not included as they did not fully answer the research question, did not refer to low-demand or marginal context or did not discuss requirements and barriers for MaaS implementation.

The included articles provide empirical and theoretical insights into various factors that positively or negatively influence the implementation of MaaS and dynamic DRT systems in spatially or socially marginalised situations.

The 66 papers included after the first screening, can be divided into two subgroups: the first group (n = 8) deals with MaaS or DRT in 'weak demand' or 'low density' contexts. The second group (n = 58) focuses on 'rural contexts'. Following the second screening, only 14 contributions met the eligibility criteria.

Specifically, for 19 contributions, it was not possible to find the full texts, a second group (n = 31) was eliminated as they do not report a clear or comprehensive description of the elements that are useful for the implementation of MaaS systems in marginal contexts, and a third group (n = 2) was eliminated as the focus is more on the effects produced by the adoption of MaaS systems rather than on the aspects that influence their implementation. Despite the significant number of papers that qualified for the second screening step of the full-text reading, only a small number were relevant to the study as they fully and comprehensively explored the topic of facilitating or hindering factors for the implementation of MaaS solutions in low-demand mobility contexts (papers where the topic was a minimal part of the proposed study were omitted).

The review decision process is presented in the flowchart below (Fig. 2).

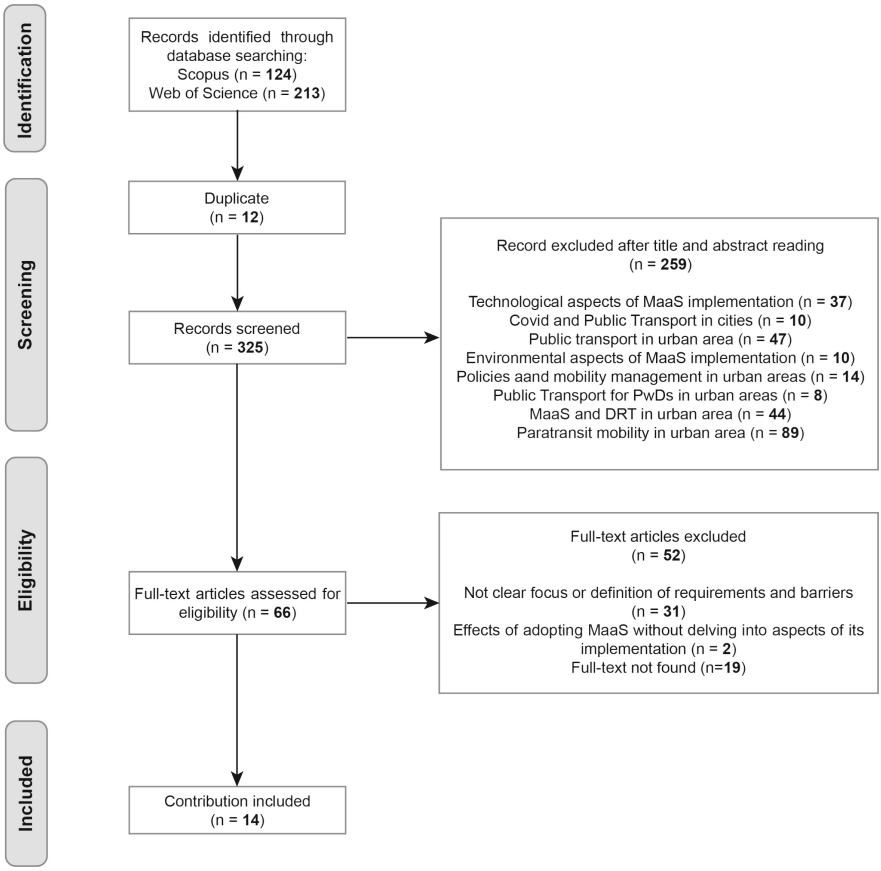

Fig. 2. Flowchart PRISMA [6]

2.4 Extracting and Data Charting Process

The full-text screening stage consisted of the extraction and systematisation of data through the development of a data extraction table based on the data charting model proposed by the Joanna Briggs Institute [5, 7].

Supplementary Table 1, reports the following data: main study features (authors, year of publication, sector/disciplinary area, geographical context of application; type of study (empirical or theoretical); population involved (age, gender, number of participants); purpose of the study; data collection methods; characteristics of study context; study outcomes, and finally the most important column containing the key findings of this review: the elements facilitating or hindering the implementation of MaaS solutions.

2.5 Collating, Summarising and Reporting Data

The last part of the analysis involved the organisation of enablers and barriers of MaaS solutions into categories of recurring themes and issues. These categories sometimes present partial overlaps. The contents that emerged are described in the discussion section.

3 Results

Although the research aimed to investigate the ten-year period from 2010 to 2023, all the included studies were published between 2020 and 2023. This is likely due to the recent emergence of the MaaS concept, which was first popularised in 2014 [1, 8]. MaaS is a recent concept and its applicability has been limited to recent years and pilot studies rather than established experiences.

Of the relevant literature, n = 13 are journal articles and n = 1 conference paper.

As previously mentioned, the majority of MaaS solution trials have been conducted in densely populated urban areas, with less attention given to peripheral or dispersed settlements.

Most of the studies were conducted in Europe. A first group of articles consists of individual specific experiences carried out in Italy (n = 3), the UK (n = 2), Greece (n = 1), Sweden (n = 1), Estonia (n = 1), and Finland (n = 1). Another group of 3 studies provides examples of mobility solutions in European rural areas by reporting a review of several case studies based on Demand-Responsive Transport (DRT) services. Lastly, a third group comprises 2 studies in rural settings in Japan.

3.1 Study Design and Approach

The study included can be divided into two categories: papers describing single experimental research taken as a case study [3, 9–15] and papers that explore more case study and, by comparison, seek to advance more general hypotheses of the phenomenon investigated, in the case of our review, factors that facilitate or hinder MaaS solutions.

From a methodological point of view, the articles are divided into: empirical study [3, 9, 10, 13–19] and literature reviews and study based on literature research [11, 12, 20, 21].

The prevalent method of data collection and management was the administration of questionnaires, also online, and focus groups [3, 9, 10, 15] and conducting semi-structured interviews [13, 16, 17].

As for the type of population involved in the studies, survey activities typically involved stakeholders such as local authorities, mobility service providers, and transport planning experts. Additionally, some studies included populations that commute to the study areas, such as inhabitants, commuters, students, and workers.

3.2 Criteria for Defining Low-Demand Contexts

The authors of this scoping review consider it crucial to identify the criteria used in the examined studies to define the study context. In general, contexts with weak transport

demand are characterised as sparsely populated territorial areas with dispersed settlements that are distant and poorly connected to main urban centres due to infrastructural deficiencies and a limited variety and frequency of connection services. They are highly dependent on private cars. Most authors associate these situations with rural areas. In particular, to better characterise the contexts, authors used indicators of population structure such as age, gender, ethnicity, and health status, as well as socio-economic status including household composition, employment status, income level, car ownership, … [9, 16]. It is important to note that the classification is objective and based on empirical evidence.

The article cites several sources [10–13, 15, 17–20] to define the degree of peripherality of the context based on daily trips to the nearest urban centres of essential services and their distances [3, 11].

Vitale Brovarone & Cotella [21] investigate rural and coastal areas, while Papaioannou et al. [14] include islands due to the low number of permanent residents and resulting low density and transport demand for extended periods of the year. Finally, only one article named "weak demand areas" [3], territories with high spatial dispersion, few inhabitants, and transport lines with many stops and many different routes. The identified areas include mountain, rural, and lowland settlements.

3.3 Studies Outcome

Although the search for scientific contributions spanned a wide time frame, the included studies were published only between 2020 and 2023. This suggests that the topic is new and gaining relevance.

Most of the studies describe requirements, recommendations, and elements that hinder the implementation of MaaS in rural settings [11, 14, 16–21]. In some studies, the authors extracted information from the papers without changing their meaning [3, 9, 10, 12, 13, 15].

4 Discussion

The included studies provide insights into the organisation of MaaS in low-demand areas. They discuss both factors that facilitate and constrain the implementation. More precisely, enablers and barriers include all factors (conditions, circumstances, qualities, attitudes, and criteria) - related to both the application context and the actors involved - that respectively act as drivers or limits for the transition to MaaS. In other words, enabling factors and barriers address the operationalisation of the concept and shed light on requirements and recommendations for the implementation of a MaaS solution.

Some studies draw useful insights for implementing Mobility as a Service in rural areas from successful experiences supported by survey and data analysis highlighting useful and effective strategies for MaaS adoption [3, 10, 12, 13, 15–17, 19]. Other articles, however, focus on different types of barriers by outlining the main challenges to be faced in these contexts [9, 11, 14, 18, 20, 21].

The analysed studies show that multiple dimensions act as facilitators and limiting factors, highlighting the complexity of the issue and the need for a multi-sectoral and multi-scalar perspective. Table 3 proposes a categorisation of recurring themes to which drivers and barriers refer: 1. Transportation planning and management; 2. Governance; 3. Policies and regulations; 4. Technological aspects; 5. Characteristics of the context.

Table 3. Systematisation of data collected: enablers and barriers of MaaS implementation in low-demand contexts

Categories	Enablers	Barriers	References
Transport Planning and management	– Densifying the network of multimodal mobility opportunities – Building sustainable operations using private-sector innovations – Using local transport operators' resources and avoiding duplication with existing PT – Integration of DDRT and flexible transport solutions – Mandate timetable coordination between different transport service providers – Active travel and green infrastructures connecting rural areas with PT nodes – Physical infrastructure to support interchanges (intermodal hubs) – Integrated, multimodal, and multi-operator ticketing system – Identify demand to design and operate a commercially viable on-demand service – Agreement on the role of different actors involved	– Unsuitable infrastructure – Service availability limited in terms of fleet capacity and hours of operation – Fragmentation of local public transport services – Cost of installing and operating DRT systems – Long journey times, lack of timetable coordination, and reliability of public transport – Difficult access to public transport networks	[3, 9, 10, 14–21]

(*continued*)

Table 3. (*continued*)

Categories	Enablers	Barriers	References
Governance	– Public stakeholder involvement and coordination – Cross-sectoral collaboration Cooperation between local authorities and transport sector to reduce the dependence on public subsidies – Local Civic organisations and commercial mobility service involvement in the design of rural MaaS – Legislative studies to address liability issues and market regulations	– Issues in collaborating with various transport modes – Lack of directives, strategic policy-making and planning – Unwillingness to collaborate and cooperate among transport providers – Liability of operators in case of disruptions	[10, 11, 13, 15–17, 19–21]
Policies and regulation	– Harmonisation of rules and procedures – Establishment of a regulatory framework to ensure fair competition and non-discrimination – Implement strategic measures and policies to encourage the shift to multimodal transport systems – Marketing strategies and information campaigns – Support and expertise of regional bodies on administrative and legislative issues – Implementation of appropriate mobility packages, work policies and incentives – Availability of financial resources from various stakeholders	– Lack of administrative expertise – Regulatory constraints and framework challenges – Lack of adequate policies, business practices and official regulations – Lack of planned policies for transition to novel mobility solutions – Lack of planned policies for transition to novel mobility solutions – Lack of directives, strategic policy making and planning	[3, 9, 11, 12, 14, 16–18, 20–22]

(*continued*)

Table 3. (*continued*)

Categories	Enablers	Barriers	References
Technological aspects	– Digital infrastructure and connectivity to exchange the necessary information – Availability of big data – Expertise in digital technologies to support transportation (i.e., booking and ride management software) – Deploying systems suitable for underpopulated areas	– Lack of ICT infrastructure (data network coverage in rural areas) – Lack of digital literacy (not everyone has the possibility or knowledge to use apps) – Lack of digital skills and infrastructure – Lack of standardised data formats and APIs – Unavailability of technological assets	[3, 9, 11, 12, 14, 16, 17, 19, 21]
Context characteristics (geographical, social, …)	– Improving the operability of systems in order to increase user-friendliness and utilisation rate – Understand the critical mass required to enable community-based services – Educational/Information interventions focusing on revealing the true cost of car ownership – Digital education for users – Accessible, available for people with different digital competency levels, easily understandable information on routing, booking, and ticketing systems – Active involvement of the future users (community engagement)	– Accessibility challenges (digital divide, lack of accessible information system for vulnerable people by rural citizens and one-time users – tourists…) – Unwillingness to accept the system by the public – Lack of user demand – Operating Costs implementation and stacking of costs (of multiple services)	[3, 12, 13, 15–21]

Transport Planning and Management

The first thematic area covers aspects related to transport planning and management such as infrastructure equipment and transportation supply characteristics. The quality of the public transport service offered is a critical factor in the effectiveness of a MaaS in low-demand areas. It is considered the backbone of the system [23] and a central factor in the maturity index of contexts regarding the implementation of such an approach [24]. However, the MaaS maturity index proposed by Goulding and Kamargianni, is not applicable in rural settings as the context conditions and transport supply differ greatly from urban settings [25].

The analysed studies identify basic transport requirements such as the importance of multimodal supply, availability of diverse and integrated travel options provided by both public or private operators including publicly subsidised transportation such as school, social and health services transportation [16, 20] but also the integrations among transport services: complementarity and coordination in mode, time and space and the flexibility of services (DDRT and similar).

In terms of barriers unsuitable infrastructure and fragmentation of local public transport services and the limited service availability in terms of fleet capacity and hours of operation may be a concern.

Also, based on the analysis of several case studies, some authors claim that the cost of installing and operating DDRT system is a major barrier. Although these services can provide mobility according to the needs of passengers and represent a valid alternative to the shortcomings of existing public transport systems, DDRTs are more expensive to implement and therefore not economically sustainable and must necessarily rely on alternative financing systems, such as public-private partnerships and public subsidies [3, 16–18, 20].

Governance

The second thematic field focuses on the factors that enable the MaaS ecosystem to function in an integrated manner.

The key governance requirements may concern the collaboration and cooperation among all parties involved at different levels, including public transport operators, private mobility service providers, infrastructure and digital service providers (i.e. electronic ticketing providers, payment service providers), policy and regulatory authorities, and finally, end-users who provide data and information on habits and preferences useful for defining the operational scenario in which the services are used [10, 11, 13, 14, 16, 17, 19]. Public authorities play a crucial role in the implementation of MaaS, setting out policy objectives serving their community and giving guidance or defining mandatory standards for the provision and quality of transport services.

The barriers may concern the lack of directives, strategic policy-making and planning [11, 19] and the transport providers unwillingness to collaborate and cooperate.

Policies and Regulation

The third category concerns strategic measures and policies to encourage the transition from private cars to multimodal transport systems as well as the legal and regulatory aspects that support service integration. On the side of policies, it is recommended to use incentives and subsidies such as combined ticket packages and reduced prices for frequent users, the introduction of inter-service ticketing (i.e. unification) with price

caps (including subsidies) [16, 18, 20]. Some authors recommend the implementation of work policies in low-demand contexts: accept as productive travel time on public transport [18]. On the regulatory side, legislative studies at various levels are needed to address liability issues and market regulations for the development of appropriate business models [14].

The main obstacles refer to the lack of administrative expertise [9, 11] and the presence of regulatory constraints [3] (long and complex authorisation procedures to obtain necessary permits or to adapt existing transport facilities).

Technological Aspects

The fourth thematic area discusses the technology, infrastructure and data availability required for the implementation of MaaS. The availability of data is crucial to its development and implementation [12] and its management and use require advanced skills in digital technologies. An efficient technological infrastructure is also necessary to enable real-time exchange of information, communications, and alerts between operators and users. An essential condition for the development of Mobility as a Service (MaaS) is the availability of static and dynamic data on the demand and supply of transport services in an open, secure, protected, and non-discriminatory form [26]. Therefore, it is important to ensure a collaborative and non-competitive climate among operators and an ethical relationship with users.

Among the requirements, the most important elements are the technological availability for the implementation of MaaS, including the implementation of complex digital infrastructures to support booking operations and ticketing [19]; the management and use of which require advanced skills in digital technologies, and new opportunities to meet the demand for mobility.

As for barriers, should be considered the lack of ICT infrastructure and data network coverage in rural areas [14], as well as the lack of digital literacy [11], not everyone has the ability or knowledge to use apps. This is particularly relevant for the elderly population who often inhabit the marginal contexts examined in this paper.

Context Characteristics

The final thematic area investigates the territorial and social conditions of the MaaS adoption context.

The authors propose social requirements that interested the understanding of the critical mass needs to enable community-based services increasing social acceptance of the proposed system in marginalised contexts and, at the same time, the importance of ensuring accessible information about routing, booking, and ticketing systems and easily understandable by people with different levels of digital competence [20].

On the other hand, from a social point of view, the authors insisted on the importance of educational interventions focusing on revealing the true cost of car ownership in order to trigger travel behavioural change.

Among the barriers some of which already mentioned in the category concerning technological aspects, the authors indicate the lack of digital literacy for the older population, related for example, to accessibility issues, where users need to be able to physically book the journey and meet the bus [21] and the lack of an accessible information system for vulnerable rural citizens [20] and a lack of demand due to the dispersed characteristics of the territorial context [12]. The authors also highlight the reluctance of residents of

low-density areas to accept the system because of higher prices and longer travel times. These shortcomings limit the competitiveness of MaaS solutions and the willingness to give up private cars [15, 20]. Therefore, the higher operating costs of MaaS systems may limit access for weaker population groups [18]. In fact, in small communities with low demand, the operating costs outweigh the accessibility benefits [16].

This study has limitations. Firstly, the topic addressed is very topical and constantly evolving which means that further research is needed to update and advance knowledge. A potential limitation may relate to the methodology, specifically, the selection of inclusion and exclusion criteria may involve some subjectivity. Additionally, the identification of several unavailable articles due to not exclusively selecting open-access articles ultimately reduced the number of included articles.

5 Conclusion

This scoping review provides a cognitive overview of the enablers and barriers to MaaS solution implementation in low-demand transport contexts.

The framework outlined offers many insights for transport planning research and practice, but it is fluid as the subject is new and constantly evolving, especially in relation to implementation cases. This limits considerations of feasibility to a few examples and to pilot studies or experiments that are still in progress, rather than to long-established experiences. A helpful source of knowledge can be the many examples of DRT systems in rural and peripheral areas, which can look back on a longer tradition and offer interesting evidence.

In addition, most of the experimentation with MaaS solutions has been in densely populated urban contexts, rather than in peripheral or dispersed settlements. However, many of the obstacles encountered in dense urban areas are also found in low-demand contexts. At the same time, marginal situations sometimes offer interesting solutions that could also be proposed in larger contexts, for example in terms of combined organisation of services [3, 12, 16], also with innovative bottom-up solutions, in terms of operational and business model as well as governance (distribution of responsibilities, competencies, economic commitments).

According to the studies analysed, financial unsustainability, lack of effective partnership between actors and extreme land use patterns are the most problematic factors to be addressed in low demand areas. There is a need for a strong and well-structured strategic planning action, taking into account several key elements, ranging from the role of the different stakeholders, among whom strong and committed cooperation is fundamental, to a thorough understanding of the context and the market, as well as communication of the potential benefits for operators, users and territories. In this sense, it is possible to identify two distinct but complementary emerging lines of action: (i) a focus on the management and organisational aspects of the ecosystem, firstly governance and business model, with the aim of optimising resources and achieving sustainable goals for communities. Following this line, all authors agree on the importance of coordination and cooperation between actors involved at different levels; (ii) an emphasis on user behaviour and mode choice, with the idea that understanding travel patterns, user preferences and the drivers of the travel decision process is paramount for any demand-driven transport system, and even more so in low-demand areas.

When it comes to technological and operational challenges, the authors seem more optimistic and confident that new and effective solutions will be easily found.

A pivotal point concerns the value attributed to DRT, regardless of the mode in which it is operated. Authors widely recognise that the perceived barriers to this transport mode are linked to the uneven distribution of demand and the characteristics of the territorial context (dispersed population, inadequate physical and digital connection infrastructures, digital illiteracy, …). At the same time, the integration of DTR into a more comprehensive MaaS system including peri-urban and rural areas would represent a real paradigm shift in terms of equal access to territorial opportunities, especially for specific categories of users with special needs, such as the elderly, people with disabilities or children.

Although all these aspects are often highlighted by the scientific community, the adoption of MaaS especially in marginal contexts remains a big challenge. This is because often, although the importance of accessibility and inclusiveness is recognised, considerations of economic feasibility or the more technological aspects of MaaS in these contexts prevail. This observation suggests the need for further research and study so that the social value associated with MaaS solutions can acquire greater importance in decision-making processes. In this respect, the framework of enablers and barriers depicted with this scoping review can contribute to increase knowledge and can address the formulation of innovative policies that support the development of MaaS, even in areas with low transport demand.

A clear starting point is the general agreement on the opportunity to adopt a context-specific and user-centric approach.

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Supplementary

Supplementary Table 1 – Data of included studies

Author(s), Year	Subject area/Journal	Study Country	Study design	Approach	Population	Studies outcome	Context under study	Requirements and Barriers
Agrimi, S. A. M., Ibn, S. M., & Bell, M. A. (2022)	European Transport Research Review	Estonia	Survey	Surveys and focus groups (ITEEP approach) (n=64 municipalities responded to the survey)	Head or deputy head of local government/Experts in strategic planning, urban planning, transport, IT or international projects	Identify mobility challenges seen as the engine and what hindering factors are preventing sustained solutions	Rural area	**Requirements:** • Technological advances • Policy about safety and economical incentives for MaaS **Barriers:** • Unreliable telephone lines • Lack of administrative expertise
Brachinger, L., Reichenberger, A., Cordelia Hawkins, S., Kickul, J., Kreiner, M., & Gadi Wimer, T. (2022)	Sustainability (Switzerland)	Europe (Austria, Slovenia, Galicia)	Mixed- methods one study design (Desk based appraisal and documentary analysis Social scale empirical research)	Semi-structured interviews	Stakeholders	Explore the benefit of well established multi level governance arrangements when introducing smaller scale mobility solutions to improve rural–urban accessibility	Rural area	**Requirements:** • Improve the operability of systematic solut to increase user friendliness and utilization rate • Create incentives, such as tax-filed price ticket packages and reduced prices for regular users • Detailing the network of multimodal mobility opportunities • Governance and coordination between stakeholders • Technological advances • Support and expertise of regional bodies • Marketing strategies and information campaigns **Barriers:** • Service availability limited in terms of fleet capacity and hours of operation • Accessibility challenges as users need to be able to physically book a journey and travel for free • Pre-registration poses an entry barrier for one-time users and, as tourists, and may be perceived as too time-consuming for infrequent local users • Financial unsustainability of DRT operation
Cristofari, C., Olivari, E., Cuneo, F., & Dalla Chiara, B. (2022)	Sustainability (Switzerland) - Social sciences/environmental science	Italy (Piedmont region)	Mixed methods 1. Survey of the literature 2. Multi criteria analysis	1. Focus group (mobility experts involved) 2. Survey	(n=1628, 70% male, 41% female)	Present the RPS-eMaaS (project in Italy that aims to develop the MaaS system at a high level of integration in a region of peripheral with public governance)	Regional scale: from the urban to rural context	**Requirements:** • Establishment of a regulatory framework that ensures fair competition and non-discrimination • Governance and coordination between stakeholders • Diversification among operators offering public transport services • Appropriate mobility packages **Barriers:** • Fragmentation of local public transport services
Crumpf, T., Cusack, A., Thrall, D., & Tenebaro, G. (2021)	ACP Conference Proceedings	Rome, Italy	Survey	Questionnaire	(n=1033 inhabitants, 502 commuters, 170 university students, 150 workers)	Description of what influences whether or not the DRT system works well, e.g. how much it costs, whether people are familiar with it and whether it is easy for them to use	Work demand area	**Requirements:** • Need for complex technologies, such as booking and ride management software **Barriers:** • Cost of installing and operating a DRT system • Acceptance by the public • Regulatory constraints (such as obtaining the necessary permits or adapting to existing transport facilities)
Eckhardt, J., Laakkonen, A., & Aapaoja, A. (2020)	European Transport Research Review	Eastern Uusimaa and Tampere, Finlandia	Overview of case studies	N.A.	N.A.	Requirements to improve accessibility of transport services in rural areas	Rural area	**Requirements:** • Collaboration between Public-Private sector • Public stakeholder involvement • Personalization of rules and procedures **Barriers:** • Lack of administrative expertise • Lack of policies • Lack of ICT infrastructure (like network coverage in rural areas) • Lack of digital literacy (not everyone has the possibility or knowledge to use apps)
Fraser, F., Kirke, D., Chen, S., & Jamil, S. (2021)	IET Intelligent Transport Systems	UK	1. Literature review 2. Overview of case studies	N.A.	N.A.	Recommendations for NMA for passengers and goods for the NMA proposed for a rural area	Rural area	**Requirements:** • Availability of "big data" • Identify demand to design and operate a commercially viable on-demand service • Understand the critical mass required to enable community based services **Barriers:** • Lack of user demand • Data availability
Fujiwaki, K., Yamada, T., Ishiguro, T., Makimura, K., & Ishida, H. (2022)	Asian Transport Studies	Japan	Empirical study (Multiple case studies more d.)	Interviews with stakeholders	N.D.	Recommendations for mobility planners to consider several perspectives (management, connecting private mobility resources and local public transport operational resources, technology, and user needs) for sustainable rural mobility	Rural area	**Requirements:** • Governance and coordination between stakeholders (Public-private partnership) • Decision-making to spend money using private sector knowledge • Collaboration with other sectors, such as tourism, to improve regional mobility • Using local transport operators' resources and avoiding duplication with existing • Integration of DRT into the road and PT network • Designing systems that match area-scale and user needs • Designing systems suitable for underpopulated areas • Increasing social acceptance **Barriers:** • Business practices and official regulations • Sustainable implementation of innovative mobility services • Operating Costs/Mobility Financing should also be considered by other sectors of the economy, such as the education, health, and welfare sectors, which rely on mobility 1 • Issues in collaboration with various layers of society
Kuik, Å., Farjo, L., & Smith, G. (2021)	Sustainability (Switzerland)	Sweden	Empirical study	Semi-structured interviews online (n=27)	Local civic organizations, local businesses, technology providers, municipalities, mobility service providers, and regional PTAs.	Give insights on how rural MaaS has been, and can be, organized.	Rural area	**Requirements:** • Active involvement of the future users • Cooperation between local civic citizens and transport bodies • Local Civic organizations and commercial mobility service involvement in the design phase of rural MaaS **Barriers:** • Unwillingness to collaborate/cooperate
McHenry, S. C. (2022)	Transportation Research Part F: Traffic Psychology and Behaviour 2022	UK	Empirical study	1. Qualitative approach: Asynchronous Online 2. Focus Groups	n=146 in total (2 - urban male n=21, female n=24, mixed n=24) 3. peri-urban male n=17, female n=20, mixed n=21 5. rural: male n=6, female n=11, mixed n=11)	Shed light on the primary challenges involved in (and therefore barriers to greater uptake of) rural social journeys made by people living in the three location types	Rural area	**Requirements:** • Machine learnable coordination between different transport service providers • Implement work policies to accept travel time as • Public transport as productive • Public transport service tailoring [i.e., unification] with prior saga (including • Educational / information interventions focusing on revealing the true cost of car ownership • Improve active travel infrastructure connecting rural areas with public transport **Barriers:** • Interesting issues of journey time, timetable coordination, and reliability of multi modal transport system • The stacking of costs (of multiple services) • Difficulties accessing public transport services/vehicles once on board
Mladenow, A., Bauernfeind, N., & Strauss, C. (2018)	Research in Transportation Economics	Europe	Cluster analysis	N.S.	N.S.	Define the role of governments in institutional, organizational, regulatory and financial frameworks in supporting rural transport services at a level that enables this access	Rural area	**Requirements:** • Active involvement of the future users (necessarily engagement is useful in order to better understand users' needs) • Partnerships and community engagement, particularly in the case of community transport (CT) organizations • Presence of transport services capable of being integrated; • Physical infrastructure to support interchanges; • Digital infrastructure connectivity to exchange the necessary information, e.g. about service delays; • The willingness of stakeholders to exchange information and to make compromises if necessary. **Barriers:** • Digital divide • Lack of incentives, strategic policy-making and planning • Lack of digital and physical infrastructure
Papathanasopoulou, C., Polydoropoulou, A., Tsilogiorgi, A., & Pagoni, I. (2022)	European Transport Research Review	Greece	Mixed method: 1. Literature review 2. Empirical study	Focus group	6 representatives from both industry and academia	Assess how the MaaS concept can work in intensely travel and racialized areas	Island and Rural areas	**Requirements:** • Legislative and financial aspect that operates level to address liability issues and market regulations • Development of adequate business models • Analysis of the Intensely Rural MaaS Ecosystem to understand the role of different actors • Technological readiness for MaaS implementation • Collaboration and cooperation among transport providers • Digital education for users **Barriers:** • Unwillingness to collaborate and cooperate among transport providers • Inability of operators to cope of disruptions • Lack of Interoperable Data Standards and APIs • Regulatory framework challenges • Unavailability of technological assets
Pellicelli, M., Saltoun, M., Rizzi, L., & Peano, A. (2021)	European Transport Research Review	Europe	Literature review	N.A.	N.A.	Study the social inclusivity, economic viability, and environmental impacts of novel mobility solutions in rural contexts based on published scholarly literature	Rural area	**Requirements:** • Flexible transport solutions, specific • Collaboration between stakeholders • Easily accessible information on scheduling and routing available for people with different digital competency levels • Integrated, multimodal, and multi-operator ticketing system offers convenience and flexibility for all user groups • Availability of financial resources from various stakeholders is a crucial success • Accessible and easily understandable information on routing, booking, and ticketing systems is extremely important for all user groups **Barriers:** • Lack of accessible information system for vulnerable people by rural citizens • Distance to the nearest stop and the need to change vehicles have the greatest effect on perceived accessibility • Lack of financial resources for transition to novel mobility solutions
Sophan, A. D. (2022).	Civil Engineering and Architecture	Japan, Kyoto	1. Literature review 2. Data analysis and estimation model (empirical study)	Questionnaire	n=500 people from rural suburban areas	Give insights useful for the implementation of MaaS in suburban areas and for the development of a sustainable community for all.	Rural and suburban areas	**Requirements:** • Integration and flexibility of transport • Strategic measures and policies should be adopted to encourage a shift away from private car to sustainable travel modes. • Inclusion of public transport in the MaaS package • Competitive price of the MaaS plans and incentives for senior citizens to give up **Barriers:** • Unwillingness to accept the system
Vitale Brovarone, E., & Cotella, G. (2020)	Sustainability (Switzerland)	Italy	Literature based research	N.A.	N.A.	Sheds light on this issue, exploring the accessibility challenges of rural areas and proposing a multilayer policy approach aimed at supporting decision-makers in improving rural accessibility across Europe.	Rural and coastal areas	**Requirements:** • Targeted policies (not one-size), in close-up policies that directly respond to the needs of targeted groups. • Careful analysis of users' need, in order to avoid spending resources on inadequate services and to understand key priorities. • Strengthen a public transport-friendly culture, addressing the main issues that today make public transport unappealing and uncle-used. • Mixed use of transport services, widening the number of user groups allowed to use services (i.e., school bus open to other user groups like students), and possibly combining passenger and freight transport (where adequate) • Strengthen local skills and roles, training and up-skilling key staff. • Information and involvement, in favor the diffusion of information **Barriers:** • Physical and social barriers linked to digitalization

N.A. = Not available; N.S. = Not Specified

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Beyond Cost-Benefit Analysis. A Methodological Approach to Access Transport Infrastructure Investments

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Abstract. European Union (EU) cohesion policy pursues the strengthening of economic, social and territorial cohesion between the different regions of the Member states. To this end, EU supports actions aimed at developing to climate-neutral economy (European Green Deal) and just and inclusive society (European Social Pillar), in the broader context of the UN 2030 Agenda for Sustainable Development. However, the choice of high-quality projects, which mainly guarantee the best cost-benefit ratio, often does not respond to the greatest impact on development and employment, and more generally the problems of marginalization and phenomena of demographic decline typical of the insular and internal areas of Italy highlighted by the National Strategy for Internal Areas (SNAI), effectively reducing the success of the overall strategy. From this perspective, the evaluation of projects based on Cost-Benefit Analysis (CBA) with the related Risk Sensitivity Analysis (EU Regulation no. 1303/2013, Annex III), although essential, requires to be associated with other tools evaluation to support the decision-making process, especially for infrastructure projects included in the Operational Programs (OP) of 2021–2027 Programming cycle. This paper fits into this concise framework with the aim of developing a comparative methodological approach of the main complementary methods of CBA. In fact, the demographic challenges, the contrast between global development and local development require a renewed approach for the financial evaluation of mobility infrastructures, in particular with a focus on Sardinia Region (Italy).

Keywords: Cost-benefit analysis · Territorial cohesion · Transport Infrastructure

1 Introduction

European Union (EU) cohesion policy has as its main objective the strengthening of economic, social and territorial cohesion between the different regions of the Member states, to be pursued by supporting economic growth and employment, scientific

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research, innovation and the competitiveness of regional production systems, sustainable development and environmental protection, in order to reduce territorial disparities and improve quality of life citizens.

The EU supports achievement of these objectives through the use of European Structural and Investment Funds (ERDF, ESF+, EMFF, Cohesion Fund, Just Transition Fund - JTF). In 2021–2027 Programming cycle their main objectives are the implementation of interventions aimed at the development of a climate neutral economy (European Green Deal) and a just and inclusive society (European Social Pillar), in the broader context of the UN 2030 Agenda for Sustainable Development. These objectives, in particular, must be achieved by implementing types of actions envisaged by the Regional Programs (PR) and the National Programs (PN) [1], approved by the European Commission (EC) to co-finance development policies on a regional and on a national scale, in line with what is established by the common provisions contained in Regulation (EU) 2021/1060 [2] and to support the 5 strategic objectives defined therein by the EC [2]. General framework of cohesion policies is completed by the Development and Cohesion Fund (FSC), whose additional national financial resources are intended for economic and social rebalancing among different areas of the country, and to support public incentives and investments.

1.1 Sardinia Region: 2021–2027 Programming Scenario

Within this programmatic scenario, the Italian Government has also approved the National Recovery and Resilience Plan (NRRP), which within the Next Generation EU, the program promoted by the EU to encourage the relaunch of the Member States following the Covid-19 pandemic 19, constitutes the set of reforms and investments to be carried out in the period 2021–2026 to pursue the objective of a greener, digital and resilient Europe through the implementation of actions consistent with the three strategic axes identified, digital transition and innovation, ecological transition and social inclusion and territorial rebalancing, on which the articulation [3] of NRRP is developed.

Extraordinary Subsequent paragraphs, however, are indented. Concentration of community and national resources made available by the NRRP and the 2021–2027 Programming, in order to create real development opportunities for the Sardinia Region and allow us to remove the diseconomies that derive from the weak and discontinuous territorial continuity for goods and passengers, presumes the ability to sustain extraordinary investments. It also requires a different approach to the evaluation of interventions to modernize and improve the internal infrastructure network (railway and road), necessary to guarantee territorial cohesion, curb the phenomenon of depopulation and marginalization of internal areas, and to increase accessibility of ports and airports, essential to ensure wider and more reliable connections with the outside world. These conditions appear indispensable to give concrete implementation to the principle of insularity, introduced into the Constitution with the modification of art.119 [4], which constitutes, together with art. 174 of the Treaty on the Functioning of European Union, foundation and legitimation of cohesion policy, since these rules require special interventions to promote harmonious development and to remove economic and social imbalances [5].

In this synthetic framework, multilevel governance supported by different degrees of institutional agreement would make it possible to overcome the use of cost-benefit

analysis (CBA) for the evaluation of the transport infrastructure interventions and the choice of investment priorities.

The aim of this manuscript is to propose a methodological approach to overcome the prevalent use of CBA, comparing with SWOT analysis the main evaluation methods complementary to CBA and evaluating the benefits that are not easily monetizable, deriving from the improvement of accessibility of transport in the framework of the objectives of the 2030 Agenda.

The manuscript is organised as it follows: Sect. 2 Materials and methods; Sect. 2.1 Material and Sect. 2.2 Methodology; Sect. 3 Results; Sect. 4 Discussion and Sect. 5 Conclusion and future development.

2 Materials and Methods

Accessibility and economic development are related to progressive globalization, which is a complex process. In fact, globalization has led to greater interconnection, facilitating single and collective mobility and the exchange of goods and services, helping to make places, goods and services more accessible to a wider audience, even in remote or developing areas. However, the relationship between economic development and accessibility is complex and multi-directional [6–8]. Economic development and accessibility are two interrelated aspects that can reinforce each other. Economic development through investment in transport infrastructure can make spatial contests more accessible and inclusive. Accessibility can foster economic development and lead to greater social inclusion, as well as a better quality of life for local communities and city users. For this reason, it is crucial to view accessibility as an investment rather than a cost [9–11]. In agreement with Rodrigue J. P. (2020) [12] accessibility plays a crucial and decisive role in economic development, equity, inclusiveness and risk management.

An efficient and capillary transport system allows, in fact, the mobility of people and goods, promoting trade, attracting investment and economic development and can also ensure spatial justice and improve the quality of life of local communities [13]. Accessibility is also a key factor in NRRP: both to facilitate trade and investment, promote employment and reduce territorial disparities, bridge the gap between urban and rural areas and improve social cohesion [14].

In particular, the resident population in Sardinia (Italy) represents is about 1 569 832 inhabitants (data updated to 1/01/2024 [15]). Compared to 2011, there was a decrease in population by 3.4%, with a birth rate of approximately 6.4 births per 1 000 inhabitants, and a mortality rate of approximately 9.8 deaths per 1 000 inhabitants. The population appears to be distributed unevenly across Sardinia: in fact the average density is about 68 inhabitants/km^2, with varying values depending on the province. The most populous provinces are the Metropolitan City of Cagliari and Sassari, which together concentrate almost 60% of the Sardinian population.

2.1 Materials

CBA is an evaluation process [16, 17] that compares the costs and benefits associated with construction, operation, and end of life [18, 19]. The CBA plays an important role in policy makers' decision-making process when it comes to prioritizing investment in transportation infrastructure consists of the following steps:

1. definition of the scope of the analysis and identification of relevant costs and benefits;
2. identification of costs and benefits and their units of measurement;
3. quantitative estimation of costs and benefits;
4. monetisation of costs and benefits;
5. intertemporal discount, aggregation of costs and benefits and calculation of the net social benefit of the policy;
6. sensitivity analysis.

However, it is very important to consider the limits of CBA. The CBA outcome can be significantly influenced by the discount rate, which is one of the main methodological limitations. In addition, the CBA adds up the costs and benefits, assuming they are homogeneous. This can be problematic for direct and indirect benefits that are not easily demonstrable from improving the accessibility of transport infrastructure, such as: economic development, equity, inclusion and risk management [20].

In this sense, cost-benefit analysis is complemented by other evaluation methods that are useful for evaluating aspects that are not always easily monetizable. In particularly complex situations, it may be necessary to use complementary methods for the different regulations in force, such as:

1. Cost-Efficiency Analysis (ACE): focuses on minimizing the costs needed to achieve a specific goal, without necessarily considering the benefits in monetary terms. Maximizing resource allocation efficiency can be achieved by using it.
2. Multi-Criteria Analysis (MCA): considers multiple evaluation criteria and assigns them a weight based on importance. It is useful when there are multiple dimensions or goals to consider, but also when you need to compare different alternatives.
3. Environmental Impact Analysis (EIA): assess the environmental effects of a project or infrastructure, focusing on aspects such as air, water and soil pollution, and biodiversity. EIA helps to identify and mitigate negative impacts on the environment.
4. Socio-economic Analysis (SEA): assesses the social and the economic impacts of a project, including job creation, poverty reduction, accessibility to services and the general well-being of the community.
5. Life Cycle Assessment (LCA): LCA examines the entire life cycle of a product or project, from production to use and end of life. It is often used to assess the overall environmental impact.
6. Risk and Uncertainty Analysis: considers the risks associated with a project and evaluates how those risks could impact the results. It is useful for making informed decisions when there is uncertainty.
7. Real Options Analysis (ROA): assesses the options available in the project, taking into account the ability to adapt to future conditions. It can be useful when decision-making flexibility is needed over time.

8. Equity Analysis: Analyze the distribution of a project's impacts on the population, with a focus on justice and equity. Helps identify whether the project benefits or harms specific groups.
9. Geospatial Analysis: uses geographic data and spatial information to analyse the location and impacts of a project in a geographical context. It is useful to assess how the infrastructure affects the surrounding area.
10. Sustainability Assessment: determine the level of economic, social, and environmental sustainability of a project. Consider the balance between the dimensions of sustainability.

2.2 Methodology

The methodology developed consists in the comparison of the main complementary assessment methods (paragraph 2.1) by the construction of SWOT analysis, integrated through two qualitative/quantitative dimensions.

SWOT analysis (Fig. 1) is characterised by a matrix 2 × 2 - exogenous (opportunities and threats) and endogenous (strengths and weaknesses) factors.

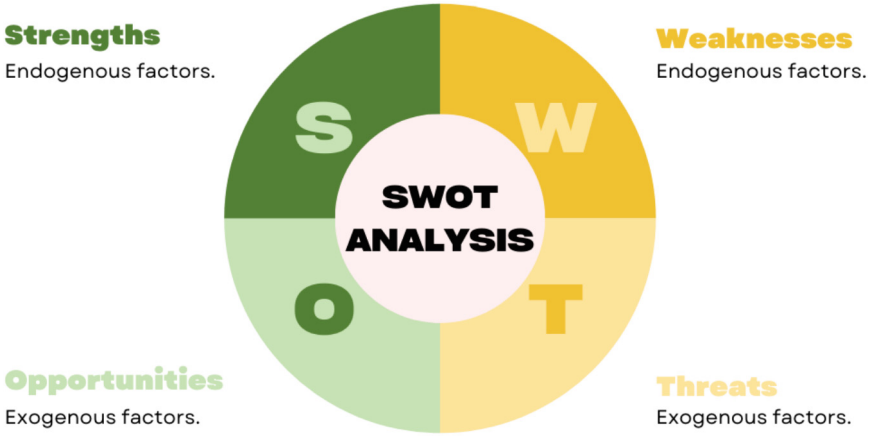

Fig. 1. SWOT analysis matrix.

The qualitative dimension is designed to link the relevant SDGs with every complementary method, while the quantitative dimension is intended to assess the level of integration of the benefits of the project not easily monetizable as: economic development, equity, inclusion and risk management (Table 2) (Fig. 2) (Table 1).



Fig. 2. Key goals not easily monetizable as: economic development, equity, inclusion and risk management (Authors: G. Balletto and M. Sinatra, 2024)

Table 1. Sardinia demography.

Province	N. of municipalities	Population (2024) [15]
Metropolitan City of Cagliari	17	418 761
Nuoro	74	197 003
Oristano	87	149 078
Sassari	92	473 236
Sud Sardegna	107	331 754
Sardinia Region	377	1 569 832

3 Results

The results of the evaluation have been reported in Fig. 3 and Fig. 4. It is highlighted that the SWOT analysis and qualitative/quantitative comparison have not included the Cost-Efficiency Analysis (CEA) method due to the similarity with CBA.

In particular, there are no methods assigned to Level 1; the average positive level (level 2) methods are: Environmental Impact Analysis (EIA) and Socio-economic Analysis (SEA); average critical level (level 3) methods are: Real Options Analysis (ROA), Equity Analysis e Geospatial Analysis: finally, the critical level methods (level 4) are: Multi-Criteria Analysis (MCA), Life Cycle Assessment (LCA), Risk and Uncertainty Analysis and Sustainability Assessment (Fig. 5).

Table 2. Integration levels of infrastructure benefits not easily monetizable from improved accessibility (Authors: G. Balletto, M. Sinatra and M. Naseddu 2024).

Level	Class	Benefits not easily monetizable from improved accessibility
1	1.00	- Economic Development, Equity, Inclusion and Risk Management
2	0.75	- Economic Development, Equity and Inclusion
		- Economic Development, Equity and Risk Management
		- Economic Development Inclusion and Risk Management
		- Equity, Inclusion and Risk Management
3	0.50	- Economic Development and Equity
		- Economic Development and Inclusion
		- Economic Development and Risk Management
		- Equity and Inclusion
		- Equity and Risk Management
		- Inclusion and Risk Management
4	0.25	- Economic Development
		- Equity
		- Inclusion
		- Risk Management

Method	*Strengths*	*Opportunities*	*Weaknesses*	*Threats*
Multi-Criteria Analysis (MCA)	Adaptability	Support for sustainable decisions	Complexity	Risks of misunderstanding
	Completeness	Development of software and tools	Subjectivity	Expert dependence
	Organizing the decision-making process.	Public participation	Data requirements	Challenges in updating data
	Inclusion of stakeholders		Difficulties in communicating the results	
Environmental Impact Analysis (EIA)	Prevention of environmental damage	Sustainable development	time and cost	Legislative changes
	Improvement of planning and design	Technological innovation	Technical complexity	Public opposition
	Stakeholder involvement	Design performance	Data limitations	Financial limitations
	Legislative compliance	Access to funding	Risk of politicisation	Climatic and environmental unpredictability
Socio-economic Analysis (SEA)	Holistic approach	Identifying new trends and patterns	Data complexity	Political and economic changes
	Basis for the decision	Promotion of social inclusion	Bias e Data limitations	Financial limitations
	Flexibility	Inter-sectoral cooperation	Required resources	Evolution of Social Crises
Life Cycle Assessment (LCA)	Structured approach	Innovation and Adaptation	Limitations in Forecasting	Speed of Environmental Change
	Process improvement	Cooperation	Subjectivity in the Analysis	Complexity and Interdependence
	Decision-making Management of Priorities	Technology and Big Data	Costs and resources	Information overload
Risk and Uncertainty Analysis	Experience in Managing Uncertainty	Emerging technologies	Limiti nella Previsione	Unpredictable Environmental and Socio-political Changes
	Advanced analytical tools	Collaboration and sharing knowledge	Limits in the Forecast	Increasing complexity
	Data Based Decision-Making	Innovation in Risk Assessment Processes	Poor Ability to Adapt	Resistance to change
Real Options Analysis (ROA)	Flexibility in Decisions	Innovation and growth	Complexity	Evolution of Financial Models
	Risk management	Portfolio diversification	Data's availability and quality	Perception of Complexity
	Evaluation of Innovative Projects	Adaptability	Subjectivity in the Estimates	Unforeseeable Market Risks
Equity Analysis	Commitment to diversity and inclusion	External collaborations	Lack of representation	Regulatory changes
	Inclusive Leadership	Innovation	Systemic barriers	Public opinion
	Education and development	Favorable legislation	Resistance to change	Growing inequalities
Geospatial Analysis	Accuracy and detail	Technological development	Technical complexity	Evoluzione Rapida delle Tecnologie
	Decision support	Interdisciplinary collaborations	Implementation costs	Data interoperability
	Innovative technologies	Growth of the Geospatial Market	Privacy and security issues	Competition and Overlap
	Multidisciplinary Applications	Sustainability and Resources Management	Data Dependence	Legal and regulatory issues
Sustainability Assessment	Commitment to reducing the environmental impact	Growth of the green market	High initial costs	More stringent environmental regulations
	Innovation	Government incentives	Internal conflicts	Volatility of resource prices
	Design performance	Collaborations and partnerships	Technological limitations	Competitive pressure

Fig. 3. Results of qualitative and quantitative evaluations - SWOT Analysis.

Metodo	*Benefits not easily monetized from improved accessibility*	*Level*	*Class*	*SDGs*
Multi-Criteria Analysis (MCA)	Inclusion	4 - Critical	0.25	3, 4, 6, 7, 8, 11, 12 e 16
Environmental Impact Analysis (EIA)	Economic Development Inclusion Risk Managment	2 - Average positive	0.75	3, 4, 6, 7, 8, 9, 11, 12, 13, 14, 15 e 16
Socio-economic Analysis (SEA)	Economic Development Equity Inclusion	2 - Average positive	0.75	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15 e 16
Life Cycle Assessment (LCA)	Risk Managment	4 - Critical	0.25	7, 12, 13, 14 e 15
Risk and Uncertainty Analysis	Risk Managment	4 - Critical	0.25	7, 12, 13, 14 e 15
Real Options Analysis (ROA)	Economic Development Risk Managment	3 - Average Critical	0.50	7, 8, 9, 11, 12, 13, 14 e 15
Equity Analysis	Equity Inclusion	3 - Average Critical	0.50	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12 e 16
Geospatial Analysis	Economic Development Risk Managment	3 - Average Critical	0.50	7, 8, 9, 11, 12, 13, 14 e 15
Sustainability Assessment	Economic Development	4 - Critical	0.25	7, 8, 9, 11, 12, 13, 14 e 15

Fig. 4. Results of qualitative and quantitative evaluations.

Level	*Class*	*Benefits not easily monetized from improved accessibility*
1 - Positive	1.00	- Economic Development, Equity, Inclusion and Risk Management.
2 - Average positive	0.75	- Economic Development, Equity and Inclusion - Economic Development, Equity and Risk Management - Economic Development, Inclusion and Risk Management - Equity, Inclusion and Risk Management
3 - Average critical	0.50	- Economic Development and Equity - Economic Development and Inclusion - Economic Development and Risk Management - Equity and Inclusion - Equity and Risk Management - Inclusion and Risk Management
4 - Critical	0.25	- Economic Development - Equity - Inclusion - Risk Management

Fig. 5. Legend of quantitative evaluations.

4 Discussion

The role of 2030 Agenda Goals, adopted by the 193 UN member countries in 2015, represents an ambitious action plan to improve the lives of communities. The 17 Sustainable Development Goals (SDGs), divided into 169 targets and 232 monitoring indicators, constitute the main framework that must also guide the design of infrastructure. The proposed qualitative dimension - SDG - allows us to obtain a picture of the sustainability objectives associated with the 10 selected evaluation methods. The proposed quantitative dimension - Level - instead allows us to obtain a picture of the levels of

integration of the main benefits (direct and indirect) deriving from the improvement of accessibility associated with the infrastructure: economic development, inclusion, equity and risk management.

From the analysis conducted, the need emerges to build a set of indicators to be associated with the development dynamics of the territory useful for evaluating the economic and social well-being of communities, which can arise from the choice of transport infrastructure projects aimed at generating development opportunities (complementary "strategic generative" evaluation methods) or defence of the needs and requirements of services ("strategic conservative" evaluation methods) for territories characterised by obvious disadvantages (geographical, demographic, etc.).

5 Conclusions and Future Development

The evaluation of the non-monetizable benefits of CBA, such as economic development, equity, inclusion and risk management was the subject of the authors' research [21]. In particular, how a transport infrastructure can bring benefits that cannot always be monetized to certain groups or regions to the detriment of others, generating differentials in economic development, equity, inclusiveness and risk management. Furthermore, it is difficult to accurately predict the future costs and benefits of a project, especially in the long term. Estimates can be affected by many variables. Decisions regarding infrastructure projects can also be influenced by political aspects, leading to choices that are not optimal from an economic point of view. Technological and social-demographic changes, the digital and energy transition [22] could also further contribute to making infrastructure projects obsolete sooner than expected, thus invalidating the CBA.

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Regional Disparity, Accessibility, and Sustainable Mobility in Insular Contexts

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Abstract. Multiple and permanent disadvantages and social inequalities often make insular contexts more vulnerable to contingent and structural phenomena. The principle of insularity, which is already recognized in EU legislation and in the Italian constitution, requires a specific political strategy and action priorities. The Sardinia Region (Italy) represents an interesting case study. As a matter of fact, despite numerous attempts to guarantee territorial continuity, the geographical isolation still represents the greatest cost for the population. Here, internal mobility is also threatened by significant gaps in transport infrastructure, especially in the inner areas. In this sense, regional issues and regional disparity are at the core of the "e.INS – Ecosystem of Innovation for Next Generation Sardinia" project - spoke 8 - Sustainable mobility which proposes a methodological approach to improve the transport offer to and from Sardinia and within the regional territory by MaaS solutions.

Keywords: Regional Disparity · Accessibility · Sustainable Mobility

1 Introduction

Multiple and permanent disadvantages and social inequalities often make insular contexts more vulnerable to contingent and structural phenomena [1].

The principle of insularity, which is already recognized in EU legislation and in the Italian constitution, requires a specific political strategy and action priorities to face the regional disparity condition [2, 3]. This is the case of the Autonomous Region of Sardinia (ARS), in Italy, which represents an interesting case study. As a matter of fact, despite numerous attempts to guarantee territorial continuity [4], the geographical isolation still represents the greatest cost for the population of over 1,500,000 inhabitants (2023). Regional disparities can be correlated to a weak extra and intra-regional continuity (mutually shaped), due to a significant gap in transport policies (air and maritime), as well as in infrastructure and supply for internal mobility, further aggravating the condition of insularity [5].

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Regional issues and regional disparity are at the core of the "e.INS – Ecosystem of Innovation for Next Generation Sardinia" project - spoke 8, which proposes a methodological approach to improve the transport offer to and from Sardinia and within the regional territory by MaaS solutions [6].

More densely populated contexts show a greater predisposition to the development and use of MaaS solutions in their traditional form, thanks to the high travel demand, the general propensity of people to integrate available mobility alternatives, and the economic convenience of both public and private operators. However, the implementation of MaaS systems in low-density settlements, such as most of the contexts in Sardinia, needs to be studied further and requires a redefinition of the model operating conditions [7, 8]. In fact, in these contexts, accessibility depends mainly on the private car, while public transport is very weak and limited to a few time slots throughout the day or seasons. Interchanges are therefore almost always obligatory.

The benefits of MaaS, which facilitates and supports travel at all stages, from planning to booking, purchasing tickets, and navigating, are particularly useful and beneficial in inner areas [29], sparsely populated areas to reduce the mobility divide (low spatial accessibility, limited mobility alternatives, high proportion of elderly people with reduced individual abilities, knowledge, and skills to travel independently, etc.). In addition, recent applications have shown that the introduction of innovative forms of mobility services can have a positive impact on the local economy, creating new jobs and business opportunities and widening the range of available transport alternatives, thus increasing the attractiveness of places, also in terms of sustainability.

In this framework, the manuscript is structured as follows: Sect. 2 - Materials, describes the study area (the ARS) and the main objective and challenges of the e.INS project - spoke 8; Sect. 3 - Method, is dedicated to the methodological approach developed for the construction of an open-source multilevel geodatabase to support the development of a transport model in Sardinia, in line with the MaaS concepts; Sect. 4 - Results, describe the main topics selected to develop the multilevel geodatabase, according to the project targets; Sect. 5 - Conclusions, reports final considerations on the research issues.

2 Materials

2.1 Study Area

The Sardinia Region is the second largest island in Italy, after Sicily. With a population of 1,578,146 inhabitants (2023), the Island records a population density value of 66 inhabitants/ km^2, among the lowest nationally.

The progressive evolution of the administrative geography [9] has led to the current configuration which consists of four provinces (Nuoro, Oristano, Sassari, and South Sardinia), a metropolitan city (Metropolitan city of Cagliari) and 377 municipalities.

Sardinia has a significant deficit in relation to the provision and competitiveness of transport infrastructure [10], which consists of [11]:

- around 9000 km of road network (State and Provincial Roads).
- 427 km of Italian railway network (RFI) [12], in addition to which the railway network managed by the Sardinian Regional Transport Company (ARST) and the tourist railway networks (Trenino Verde) should be considered.

– 8 ports administered by the Port System Authority of the Sea of Sardinia (Cagliari, Olbia, Porto Torres, Golfo Aranci, Portovesme, Oristano, Santa Teresa di Gallura and Arbatax).
– 3 international airports (Cagliari, Olbia, and Alghero).

The past, present and future of the Sardinia Region are closely linked to the "transport" issue, in relation to external connections, and, above all, to internal connections on the island [32]. The transport system has significantly influenced various development opportunities [13], as well as the rise of tourist destinations, which nowadays face seasonal concentration of tourist flows [14].

Despite numerous attempts to guarantee territorial continuity [15], the geographical impedance still represents the greatest cost for both inhabitants and city users (Fig. 1).

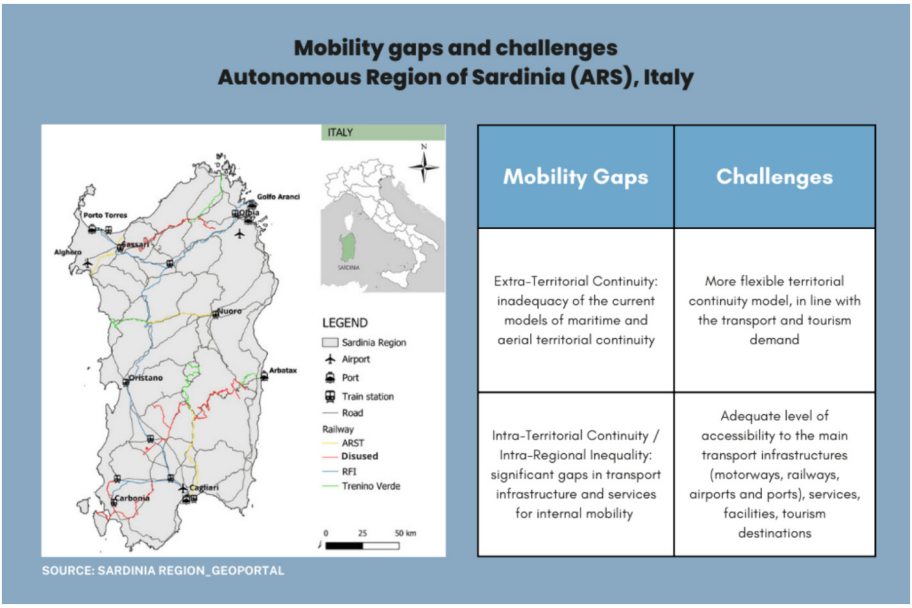

Fig. 1. Mobility gaps and challenges in the ARS (Italy). Author: Mara Ladu

Regional disparities can be correlated to a weak extra and intra-regional continuity (mutually shaped), due to a significant gap in transport policies (air and maritime), as well as in infrastructure and supply for internal mobility, further aggravating the condition of insularity [5]. As a matter of fact, transport services are essentially limited to a few rail connections (due to the limited extent of the network) and public road transport on extra-urban routes, operated by the regional company ARST and a few private subsidized companies. Urban public transport system is available in major cities. The island's settlement structure, characterized by the strong dependence of the smaller centers on the main urbanized areas (Fig. 2), has determined the structure of the transport services, which become more sparse (in terms of trips and frequency) as the distance

from the main attractions increases, making public transport less convenient and non-competitive with the private car.

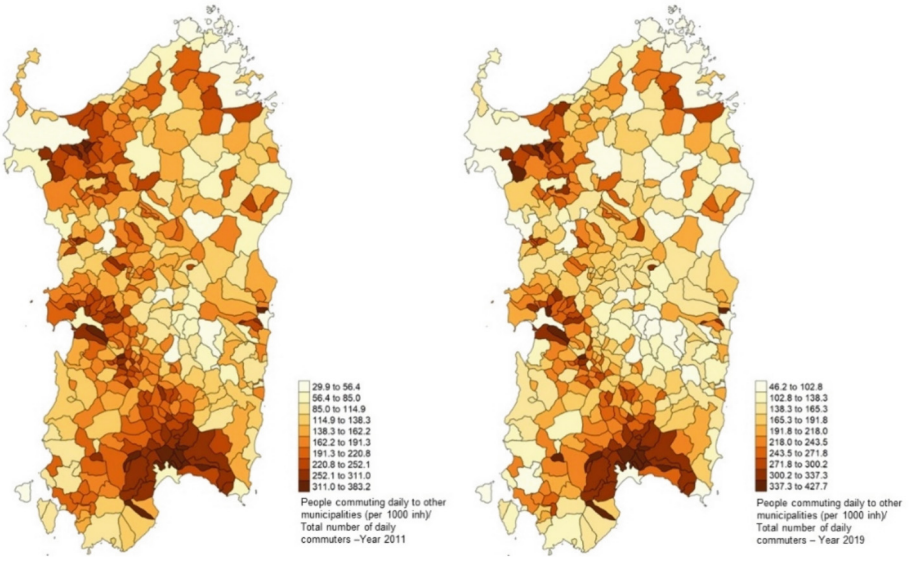

Fig. 2. Commuting flows (data source ISTAT Census 2011 and 2019). Author: Tanja Congiu

Furthermore, as in the national context, demographic decline, and the aging of the population [16], especially in the inner areas (Fig. 3), represent regional issues closely connected with regional continuity (extra and intra).

In this sense, the quality of transport infrastructures and services (road, rail, maritime, and air transport) becomes a determining factor in reducing travel times, improving internal connectivity [14, 30], and guaranteeing the right to mobility.

Extra and intra-regional continuity represents one of the main issues for the future of the Sardinia Region, according to the principle of insularity [17] recently established by the new article 119 of the Italian Constitution [2], which represents one of the main results of a growing cultural, social, and political awareness of the peculiarities and diversity of the insular contests [18, 19].

Regional issues and regional disparity are at the core of the e.INS project, which proposes a methodological approach to improve the transport offer to and from Sardinia and within the regional territory by MaaS solutions.

2.2 The Challenges of the e.INS Project – spoke 8

The e.INS project - spoke 8, funded by the Italian Ministry of University and Research under the Next-Generation EU Programme (National Recovery and Resilience Plan (PNRR) [20], is part of the broader technical-scientific debate of sustainable multimodal mobility in the framework of the energy and digital transition, with reference to modal

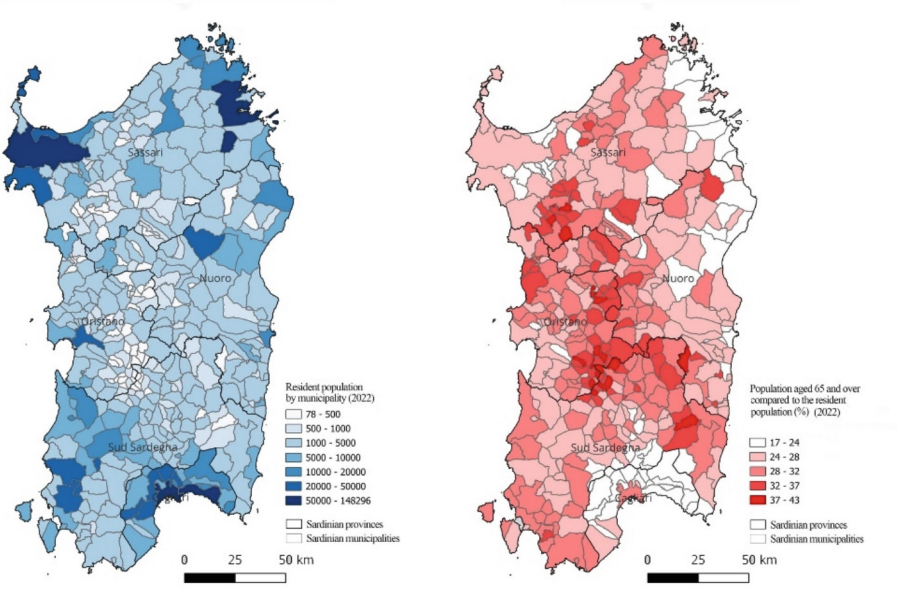

Fig. 3. Resident population by municipalities and percentage of the population aged 65 and over (data source ISTAT). Author: Mara Ladu

integration in the interconnections between Sardinia and the rest of Europe, and within the same regional territory.

In line with the Mobility as a Service (MaaS) perspective [21–24], which will increasingly influence accessibility, mobility and transport, the project evaluates the Sardinia transport system, at different territorial scales (urban, metropolitan, local, and regional) to encourage a modal shift from private cars to more sustainable modes of transport. Particular emphasis is placed on the integration of mobility services, supported by digital platforms for both management and use. A first focus is on accessibility to Sardinia airports, the main passenger gateways to the island. In 2023, passenger movements (arrivals and departures) at Sardinia airports were over 9 million, compared to around 5 million recorded at the ports.

The integration between urban planning, transport systems and ICT represents a prerequisite for a multimodal transport model that combines mobility demand and supply with which to inform a MaaS system. In this perspective the first activity concerns the development of a comprehensive knowledge base of transport demand and supply in Sardinia, which will be used to support the subsequent transport planning and the MaaS solution. More specifically, as summarized in Fig. 4, the research project envisages the following stages, including activities and associated milestones:

– a multi-level geodatabase concerning transport supply (infrastructures capacity, services frequency, and networks coverage), land use structure, provision, and spatial distribution of urban and territorial facilities (Stage I)
– a transport model, i.e. a demand and supply model for sustainable multimodal transport to/from Sardinia's airports (involving local community, city user, tourists), which

also contemplates the seasonal nature of the tourism development model consolidated in the Sardinia Region (Stage II)

– a Mobility as a Service system of the regional transport system to encourage the modal shift from private vehicles to sustainable multimodal mobility options, with particular attention to the promotion of integrated services by a single ticket (Stage III)
– a tool for evaluating the overall impact of the proposed research and a method for transferring the results into practice, making the developed outcomes available to the different target audiences. Evaluation, transfer, and dissemination activities involve private and public subjects to promote a regional sustainable transport planning and an innovative and integrated mobility, especially in the connections between airports and the regional territory (Stage IV).

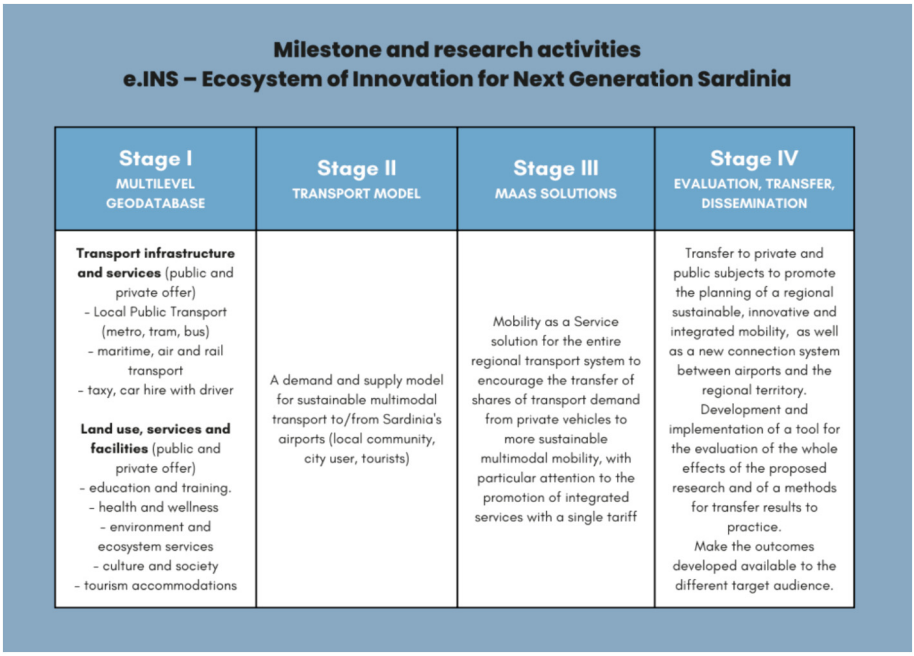

Fig. 4. The e.INS – Ecosystem of Innovation for Next Generation Sardinia project. Milestones and research activities. Author: Mara Ladu

This article describes the first stage of the research.

A methodological approach has been developed for the construction of an open-source multi-level geodatabase (Stage I) to support the development of a demand and supply model for sustainable multimodal transport to and from Sardinia's airports (Stage II), with the aim of creating an airport MaaS solution to meet the needs of residents, tourists, and city users (Stage III). These objectives are in line with the ambition to make the connections between the airport and the tourist destinations more efficient

and sustainable, including consolidated (coastal tourism), and emerging and potential destinations (slow tourism) [25, 31].

The definition of the methodological approach was supported by a theoretical study of the MaaS system from different disciplinary perspectives, aimed at highlighting the multiple aspects to be considered in the development and implementation of the new concept of mobility.

An exploration of enablers and barriers to the implementation of MaaS solutions was carried out to guide the multi-dimensional analysis of the current organization of the regional transport system and to address further integrated policies and interventions aimed at supporting the shift towards the new multimodal transport system. According to the literature, one of the main barriers is the lack of operator commitment and the consequent need to establish effective partnership between the actors involved even with innovations in organizational processes [27, 28].

Closely related to these issues was the analysis of the legal and normative framework with which to approach the design and management of both transport infrastructures (the main Sardinian gateways) and innovative multimodal mobility services, which require cooperation and coordination between all the public and private actors involved, according to their respective roles, competences, and tasks. The in-depth analysis of the legal and regulatory aspects supporting the integration of services and the regulation of the market is a prerequisite to ensure the effective implementation and governance of the MaaS ecosystem in Sardinia.

3 Method

The manuscript proposes a methodological approach to develop a dashboard framework to support MaaS sustainable solutions, according to the eINS project - S poke 8 objectives. More precisely, a multi-level geodatabase (Stage I) is intended to achieve objectives related to the development of a demand and supply model for sustainable multimodal transport to/from Sardinia's airports (local community, city user, tourists), to support the construction of an airport MaaS, of which the conceptual framework is reported (Fig. 5).

Specifically, the construction of the database is divided into the collection and systematization of information (open data) relating to various topics, that characterize the insular socio-economic context of Sardinia. Data has been implemented in accordance with INSPIRE KNOWLEDGE BASE EU Directive (2007) [26]. The standardization structure scheme is as follows: Data (code, name, source), Spatial dimension (unit and global dimension), File (format, date, and frequency update).

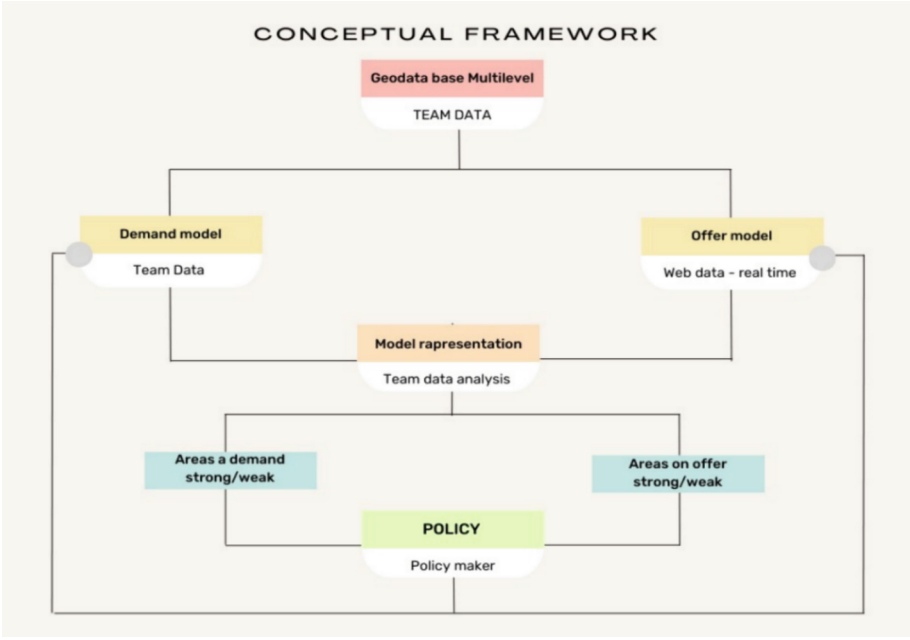

Fig. 5. Dashboard framework to support MaaS sustainable solutions. Author: Ginevra Balletto

4 Results

According to the methodology, a set of data has been implemented and systematized in a multi-level database, preparatory for the construction of a demand (local community and city user) and supply model for sustainable multimodal transport in the island context, to support the construction of MaaS solutions to improve connections to and from Sardinia's airports.

The construction of the Sardinia multi-level geodatabase consists of the collection and systematization of open data (dynamic and static data) relating to various topics, characterizing the insular socio-economic system along with the current provision of infrastructural networks and transport services. The cartographic bases used are: Openstreetmap, Google Earth, MyMaps, etc. with the network of roads, railway and internal maritime routes also represented.

In this section, the main topics selected to develop the multi-level geodatabase (Stage I) are described. Figure 6 shows the main topics selected for the achievement of the targets M001-M004 defined in the project, which concern the construction of a dashboard framework to collect, analyze and monitor the following aspects:

– M001: dynamics of passenger demand to/from Sardinia
– M002: land use (spatial distribution of services and facilities) in Sardinia
– M003: transport system supply to/from Sardinia (extra-regional continuity)
– M004: transport supply in the Sardinia Region (intra-regional continuity).

More precisely the list of the main topics of the collected data for the targets M001 and M002 is reported below:

- Land use: urban services, productive activities, etc.
- Population: population and housing census; Local labor systems; incomes of the population
- Consumption of water and electricity by sector, on a municipal scale
- Production of urban waste, on a municipal scale
- Passenger traffic (air and maritime transport): number of arrivals and departures to and from Sardinian ports and airports
- Tourist movements: number of arrivals and presences, on a municipal scale
- Accommodation facilities: number and type of tourist accommodation facilities, on a municipal scale
- Education. Schools: number and type of schools and number of students, on a municipal scale; University: number of students in Sardinian universities
- Health services: number of hospital beds; type of hospital emergency network structures.

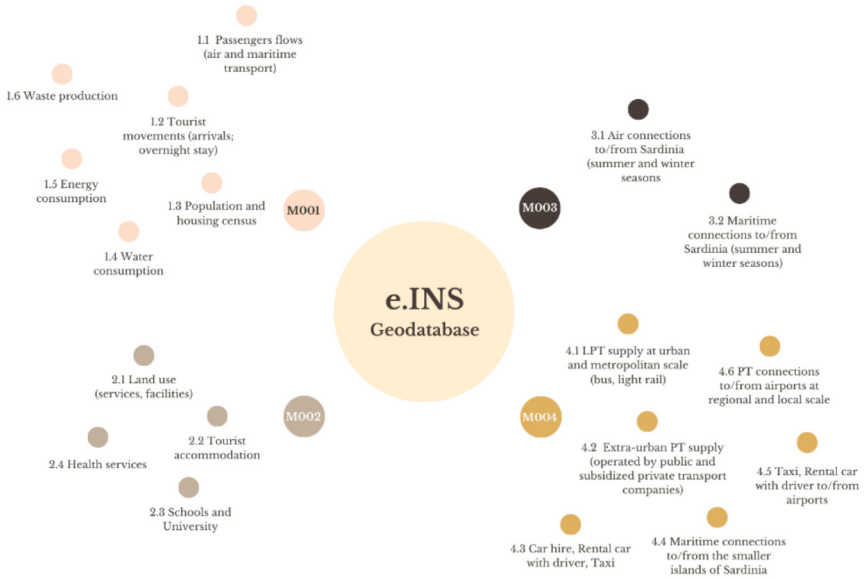

Fig. 6. Framework of the main topics of the multilevel geodatabase. Authors: Ginevra Balletto and Mara Ladu

Target M003 and M004 concern the depiction of the transport supply to and from Sardina and within the island.

The following data were therefore collected and processed to feed the dashboard and develop the transport demand and supply model:

- Data on air and maritime connections to/from the main Sardinian gateways for the whole year

- measurement of the infrastructural network capacity and connectivity
- coverage and frequency of transport services (considering both public and private operators)
- accessibility of the main attractors (transport nodes and urban amenities).

This analysis reveals inequalities between areas in terms of transport provision and, together with the distribution of demand, provides the basis for planning new solutions.

5 Conclusions

Mobility as a Service (MaaS) is an emerging paradigm that offers an alternative to owning a private vehicle. Through a digital platform, users can access a variety of means of transport (individual and collective) by paying only for actual use.

The future of MaaS is full of potential. The evolution of MaaS towards a more integrated, sustainable, and personalized system will have a significant impact on people's lives and on the cities and regions of the future.

MaaS solutions born in metropolitan cities have gradually found application in rural areas, university campuses and large events. Only recently MaaS solutions have been applied in island contexts, Sardinia as a case study.

Insular contexts present specific challenges and opportunities for MaaS implementation. The main challenge derives from the distribution of the population in Sardinia, characterized by a concentration in coastal and urban areas, with a progressive depopulation of inland areas. The aging population and immigration are two factors that influence regional demography.

Sardinia is a tourist destination of primary importance on the international scene, with consolidated attractiveness and constantly growing demand, with the increase in tourist flows (arrivals and presences) representing an opportunity for MaaS solutions.

The multi-level geodatabase is a fundamental component for MaaS solutions. It plays a key role in the formulation and operationalization of innovative and sustainable transport solutions, allows the development of analytical methods and tools with which to detect spatial and temporal disparities and similarities between areas in terms of mobility capital of urban populations (local community, city users as well as tourists) and their corresponding mobility behaviors.

The definition of geographies of accessibility and mobility at regional level is a valuable support for integrated transport and urban planning. It helps to identify low and high demand contexts, reveals travel demand segments and gaps with network coverage and service frequency, highlights inefficiencies.

This context-specific knowledge can support an important innovation process in the organization of mobility and land use in Sardinia. It addresses tailor-made solutions, informs urban policies aimed at balancing territorial relationships and facilitates the establishment of agreements between actors starting with new models of cooperation and partnership in mobility management.

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Downscale Agenda 2030 (SDGscale 2024)

The Role of Spatial Proximity and Urban Functions Density in the Sports Mega Events

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Abstract. The Sport Mega Events (SMEs) are large-scale events that involve many spectators, participants and organizers. The assessment of accessibility and the related management of people, public and private vehicles flows for stadiums during SMEs, is a major challenge for mobility management and the containment of environmental interference, in order to ensure safety and health for the local community.

In the Italian context there is a lack of collaborative convergence between the technical-scientific community and the Italian National Olympic Committee (CONI): the latter refers to a regulation (CONI standards for sports systems, 2008) obsolete for accessibility, thus highlighting the need for improvement and adaptation to current needs. In addition, increased community awareness of the crucial importance of sustainable mobility, energy efficiency and reduction of air pollution, also motivated by the 2030 Agenda objectives, highlights the need for gradual changes in the lifestyle of the communities themselves.

The authors' research, already engaged in the topic, fits into this synthetic framework, developing a Functional Urban Area Index (FUAPI) in 2023 which allows us to represent ex-ante scenarios based on the spatial distribution of the local community and the density of urban functions.

The aim of the paper is to evaluate and compare FUAPI for the different stadiums of the national territory, in particular the eleven stadiums candidates for the European Football Championships 2032. This allows it to represent a picture of ex-ante scenarios, which play a role in the definition of urban planning and transport-mobility actions for the SMEs' organization.

Keywords: Spatial Proximity · Functional Urban Area · Sport Mega Events

1 Introduction

Nowadays, stadiums are not only simple structures designed to hold crowds for sporting events, but they also serve as spectacular frames for the events themselves.

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Through their dynamic evolution, stadiums evolved from modest playgrounds to multi-purpose arenas that host not only sporting events, but also artistic and cultural performances [1]. They therefore become, in addition to places where sporting competitions take place, cultural and social epicenters that demonstrate the unifying power of sport. The organization of Sport Mega Events (SMEs) is a complex process and includes multiple issues that must be addressed: definition, mediation, urban development, economics, politics, legacy, impact, and resistance to their acceptance. Moreover, the planning of such events is often incompatible with the principles of sustainability and the objectives of the 2030 Agenda [2, 3].

This manuscript is part of the research carried out by the authors in 2023 [4]. The aim of this paper is the application and evaluation of the Functional Urban Area Proximity Index (FUAPI) for the Italian stadiums candidates to host the European Football Championships of 2032. This index allows the representation of SMEs ex-ante scenarios, represented before mega sports events are realized, calibrated on the local population distribution and the density of the different urban functions, supporting urban planning and local public transport in choosing locations and/or improving urban services closely related to the residence.

The manuscript is organized as follows: Sect. 2 provides a literature review on the concepts of stadium and SMEs; Sect. 3 focuses on the method; Sect. 3.1 describes the study area and Sect. 3.2 provides the related data; Sect. 4 is dedicated to the case study and the application of the method; Sects. 5 and 6 discusses respectively results and conclusions of the study.

2 Literature Review

2.1 Stadium and Sports Mega Events in the Urban Context

After the crisis following the Covid-19 pandemics, many studies have focused on the enhancement of urban society and services closely related to residence [5–7]. These services are designed to ensure that everything you require daily can be reached within a 15–20 min walk [8, 9]. Spatial proximity has enabled the generation and/or consolidation of a proximity of neighbourhood relations: in fact, social relations, mutual care and the enhancement of common goods are the main result of the neighbouring city - the so-called city of 15 min. The theme of sports mega events is evident in this context: many studies have been carried out on the effects that they have on space and on the communities hosting them. By virtue of their scale, level of financial investment and media coverage they can produce positive effects (economic growth and urban regeneration [9]) but also negative effects on the host community [10]. The organization of a Sport Mega Event (SME) requires multiple issues to be addressed, including territorial governance, infrastructure planning, the related environmental impacts as well as the complex resistance to housing them [11]. Thus, the economic and social spheres are both affected by these events. These impacts are defined as those “that have a potential impact on the quality of life of local residents” [12]. Most of the SMEs, in fact, take place inside stadiums, located in urban contexts with consequent impacts on local communities. They play a fundamental role in the organization and success of the event itself: stadiums not only host competitions, but they also offer integrated services and facilities

to handle the large number of participants. Stadiums, in fact, were born as 'factories of sporting events' and have developed on the one hand with the evolution of sport, on the other with the growing interest in sport supported through the link between sponsor and media, but also as a consequence of the sport business industry [1, 13].

In the specific case of the Italian stadiums, Fig. 1 describes the three main phases [14] of the stadium model, which is closely related to the spatial settlement model.



Fig. 1. Italian stadium Generation (Author: Sinatra M., 2024; Source: Balletto, G., Borruso, G., Tajani, F., & Torre, C. M. (2018) [14]).

To ensure the safety and health of communities [15], sustainable mobility must contain environmental interference (noise, air etc.), which is an important challenge in the SMEs' organization [16–18], also in the management of vehicular and pedestrian flows, with a special focus on the management of accessibility.

The difficulty with assessing the latter arises from taking into account not only the average time for individual stages of the journey to access stadiums, but also the levels of congestion and/or traffic regulation systems.

3 Materials and Methods

The method is an advance of the research previously carried out by the authors. The aim of the research was to develop a proximity index, based on the distribution of the resident population, spatial proximity [4], and accessibility, which could support the planning of Mega Sports Events [4]. In this paper, the method has been improved: the aim, in fact, is to develop a methodological approach that allows the construction of a proximity index,

based on the distribution of the local residential community and the density of elements to which certain urban functions are attributed, identified through the FUA sub-units.

The point data model, in particular, was transformed into a three-dimensional continuous density surface by using the Kernel Density Estimation function. Therefore, the Functional Urban Area Proximity Index (FUAPI) represents the sum (*1-n*) of the Kernel Density Estimation area performed on the different functions of the i-th data set, and spatial proximity (k_i) all multiplied by the weight w_i [4]:

$$\text{FUAPI} = \frac{1}{n}\sum_{i=1}^{n} w_i k_i \tag{1}$$

Specifically, k_i can be described by the following formula:

$$k_i = \frac{cluster\ area\ of\ KDE_i}{spatial\ proximity} 0 \leq k_i \leq 1 \tag{2}$$

where:

- cluster area of KDE_i represents the area obtained through the Kernel Density Estimation of the i-th data set;
- spatial proximity is the buffer area with a radius of 1 500 m, calculated by the service from which attractiveness is evaluated.

The weight w_i can be expressed as the difference of the resident population within the spatial proximity area and the population living in the i FUA analyzed, all related to the population of spatial proximity:

$$w_i = \frac{\text{population of spatial proximity} - \text{population of} FUA_i \text{ class}}{spatial\ proximity} 0 \leq w_i \leq 1 \tag{3}$$

FUAPI provides an indication of the current situation of the proximity area from which the attractiveness of the service is assessed (ex-ante scenario).

To asses the scenario that would occur following the performance of a SME (ex-post scenario) it was evaluated, in percentage terms, the relationship between the people who could attract the event (turnout) and the resident population within the spatial proximity, defined as Carry Capacity:

$$CC = \frac{turnout\ of\ an\ event}{population\ of\ spatial\ proximity} 0 \leq CC \leq 100 \tag{4}$$

Table 1 shows different scenarios for FUAPI and Carry Capacity.

Table 1. Possible scenarios, classified for the respective level, FUAPI and Carry Capacity class (Authors: Balletto G. and Sinatra M, 2023).

Level	Functional Urban Area Index (FUAPI)		Carry Capacity (CC)	
	Class [0–1]	Scenario	Class [%]	Scenario
1	1–0.76	Positive	$60 \leq CC \leq 100$	Mid-high positive
			$60 < CC \leq 45$	Average positive
			$45 < CC \leq 30$	Average critical
			$30 < CC \leq 20$	Mid-high critical
			$CC < 20$	Critical
2	0.75–0.51	Average positive	$60 \leq CC \leq 100$	Mid-high positive
			$60 < CC \leq 45$	Average positive
			$45 < CC \leq 30$	Average critical
			$30 < CC \leq 20$	Mid-high critical
			$CC < 20$	Critical
3	0.50–0.26	Average critical	$60 \leq CC \leq 100$	Mid-high positive
			$60 < CC \leq 45$	Average positive
			$45 < CC \leq 30$	Average critical
			$30 < CC \leq 20$	Mid-high critical
			$CC < 20$	Critical
4	0.25–0.00	Critical	$60 \leq CC \leq 100$	Mid-high positive
			$60 < CC \leq 45$	Average positive
			$45 < CC \leq 30$	Average critical
			$30 < CC \leq 20$	Mid-high critical
			$CC < 20$	Critical

3.1 Study Area

The UEFA (Union of European Football Associations) European Football Championship 2032, more commonly known as EURO 2032, will be the 19th edition and will involve the male national teams of UEFA member associations. Between June and July 2023, Italy and Turkey will host the competition. For Italy it will be the fourth time that the matches of the European Championship will be played in its stadiums (EURO 1968, EURO 1980 and EURO 2020), while Turkey will host the championship for the first time.

For this reason, the study area is therefore represented by the Italian cities () candidate to host the European football championships 2032 (Bari, Bologna, Cagliari, Florence, Genoa, Milan, Naples, Palermo, Rome, Turin and Verona) (Fig. 2).

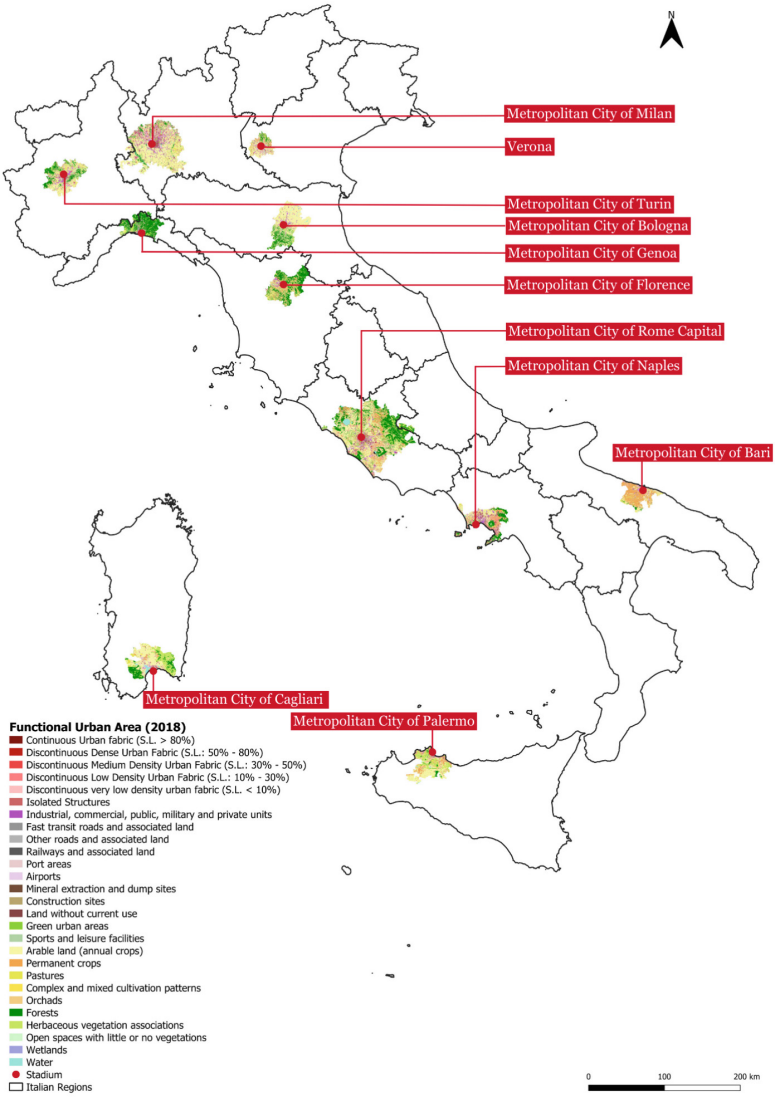

Fig. 2. Italian cities candidate to host the European Football Championship 2032 and related Functional Urban Area (Author: Sinatra M., 2024).

3.2 The Data

The dataset used in this manuscript consists of different layers (Table 2). In particular, following a careful review of the literature, the following data were used:

1. Urban Atlas - Copernicus: Functional Urban Area (2018 edition) [19]. Specifically, from this dataset it was possible to extract information about the urban fabric, classified according to 788 functional urban areas at European level. Italy's classification includes 27 functional urban areas.
2. Permanent census of population and housing [20]. This dataset was used to identify the resident population for different land use classes. Although the Copernicus dataset provides a population estimate, it was chosen to interpolate census section level data with land use classes in order to obtain more recent and reliable data. The following table summarizes the data used.

Table 2. Datasets.

ID	Dataset	Open Data	Source
01.1	Sports and leisure facilities	✓	FUA (Copernicus, 2018 Edition)
01.2	Continuous urban fabric (IMD > 80%)		
01.3	Dense urban fabric (IMD 30–80%)		
01.4	Low density fabric (IMD < 30%)		
01.5	Industrial, commercial, public and military units		
02	Permanent census of population and housing	✓	ISTAT, 2021

4 Case Study: Italian Stadiums Candidates for European Cup 2023

Italy submitted its candidacy for hosting matches in its stadiums together with Turkey for the 2032 European Football Championship. For this reason, it was chosen to apply the methodological approach to the 11 Italian candidate cities to host the EURO 2032 matches. Demographic statistics for metropolitan cities (Except for Verona, which is not a metropolitan city) [1], information on the urban/administrative fabricand the relative capacity of the stadiums can be found in Table 3.

Table 3. Summary of demographic statistics and urban/administrative infrastructure's information. Green indicates: metropolitan city, urban stadium and the presence of the metro or railway. Instead, red indicates: that the city is not a metropolitan city, the stadium is not an urban stadium and the absence of metro or railway.

City	Population (1/01/2023) [1]	Pop. density [pop/km^2]	Metropolitan City	Urban stadium and capacity	Train or Metro
Napoli	2 980 338	2 528		54 726	
Milano	3 228 006	2 049		75 817	
Roma	4 227 059	788		72 698	
Genova	816 606	445		36 599	
Cagliari	420 364	337		30 000	
Torino	2 204 632	323		41 507	
Bari	1 225 048	317		58 270	
Firenze	988 194	281		43 147	
Bologna	1 014 124	274		38 279	
Palermo	1 204 189	240		36 365	
Verona	256 049	199		39 211	

For the geospatial representation, the cities that presented the most significant results were chosen. The first selected city is Bari (Fig. 3) as the FUAPI turns out to be the lowest (FUAPI = 0.48 - level 3). The second city selected is Verona (Fig. 4), which has a high FUAPI level (FUAPI = 0.82 - level 1), even though it is not a metropolitan city. The following geospatial representations illustrate the different KDE and spatial proximity (R = 1 500 m). In particular, as regards the analysis of KDE, it was used a quadratic KDE with a radius of 500m and cell size of 25 m, applied to the following parameters and with the results as indicated:

- sports and leisure facilities (Fig. 3a and 4a);
- continuous urban fabric. S.L. > 80%(Fig. 3b, and 4b);
- discontinuous dense and medium density urban fabric- SL 50–80%) (Fig. 3c and 4c);
- discontinuous medium and low density urban fabric - 10–50%, (Fig. 3d and 4d);
- discontinuous medium and low density urban fabric - 10–50%, (Fig. 3d and 4d);
- industrial, commercial, public, military and private units (Fig. 3f and 4f).

5 Result and Discussion

The analysis was carried out on the candidate Italian cities to host the European Football Championship 2032. The proposed method based on FUAs made it possible to obtain a proximity index on the distribution of the local residential community and on the density of urban functions. The density was calculated using the Kernel Density Estimation function. The summary results for the cities (Bari, Bologna, Cagliari, Florence, Genoa, Milan, Naples, Palermo, Rome, Turin and Verona) are shown in Table 4. In particular, the cities that have FAUPI level 1 scenarios are: Genoa, Turin and Verona; level 2 are: Bologna, Cagliari, Milan, Naples, Palermo, Rome and Florence; the only city with a level 3 rating is Bari.

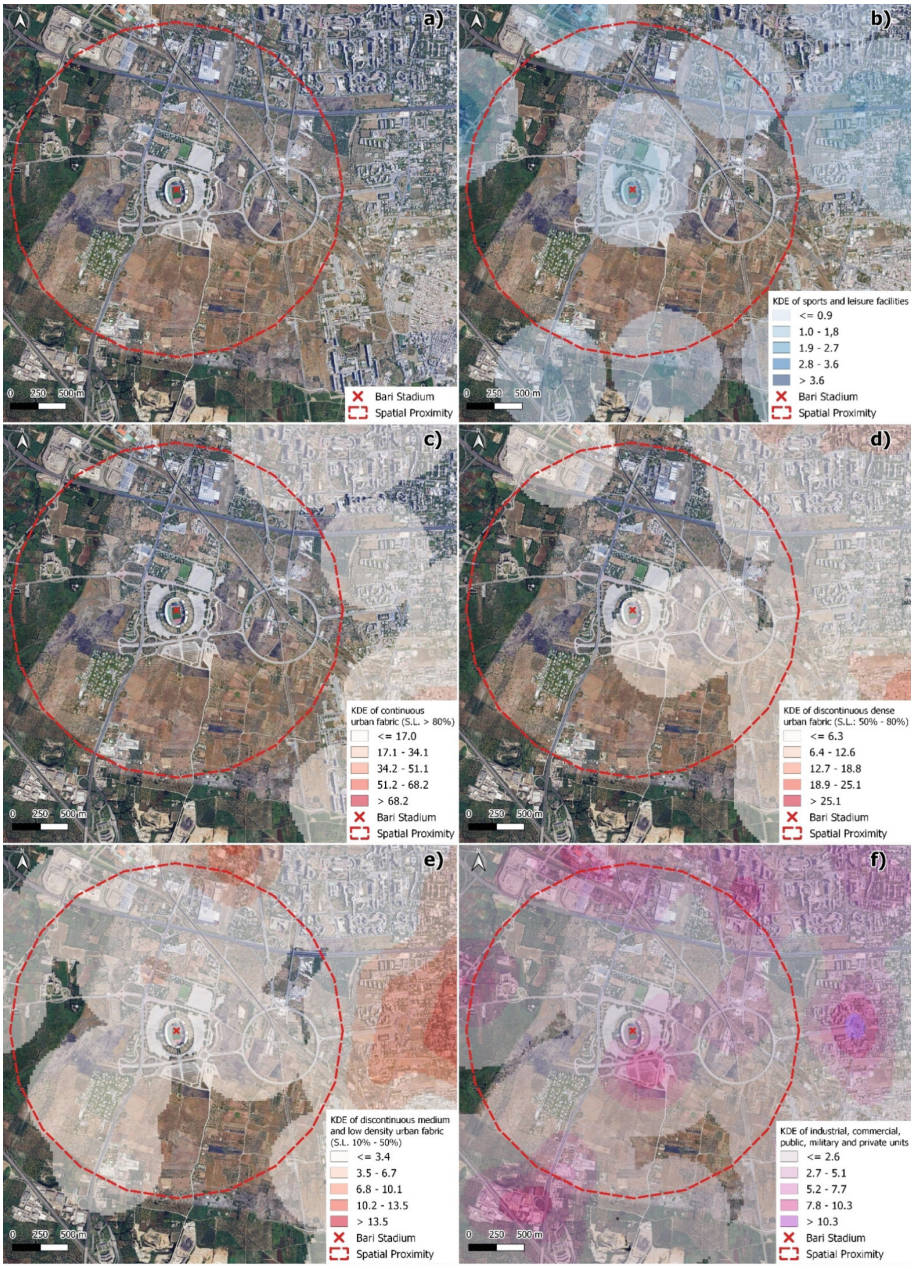

Fig. 3. Bari - Kernel Density Estimation and spatial proximity (Author: Sinatra M., 2024).

For each scenario we then proceeded to determine a set of policies (Table 5).

Table 4. Functional Urban Area Proximity Index results.

City	ID FUA_i class	Pop. of FUA_i	Pop. of spatial proximity	Stadium capacity	w_i	Cluster area of KDE [m^2]	Spatial proximity [m^2]	k_i
Bari	01.1	36	3 561	58 270	0.99	2 520 820	6 952 882	0.36
	01.2	0			1.00	199 169		0.03
	01.3	11			1.00	2 298 318		0.33
	01.4	11			1.00	5 338 959		0.77
	01.5	71			0.98	6 549 302		0.94
$FUAPI_{Bari}$		**0.48 (level 3)**						
Bologna	01.1	262	51 756	38 279	0.99	3 558 822	6 952 676	0.51
	01.2	11 662			0.77	5 546 669		0.80
	01.3	22 218			0.57	6 089 854		0.88
	01.4	6 456			0.88	6 892 694		0.99
	01.5	3 953			0.94	6 715 670		0.97
$FUAPI_{Bologna}$		**0.68 (level 2)**						
Cagliari	01.1	31	23 187	30 000	1.00	3 447 652	4 668 999	0.74
	01.2	5 960			0.74	3 882 587		0.83
	01.3	9 520			0.59	4 167 487		0.89
	01.4	3 784			0.84	3 950 009		0.85
	01.5	1 497			0.94	4 640 632		0.99
$FUAPI_{Cagliari}$		**0.70 (level 2)**						
Florence	01.1	437	59 519	43 147	0.99	3 796 317	6 952 671	0.55
	01.2	36 263			0.39	6 113 453		0.88
	01.3	16 525			0.72	6 659 877		0.96

(*continued*)

Table 4. (*continued*)

City	ID FUA_i class	Pop. of FUA_i	Pop. of spatial proximity	Stadium capacity	w_i	Cluster area of KDE [m^2]	Spatial proximity [m^2]	k_i
	01.4	1 631			0.97	5 477 742		0.79
	01.5	3 490			0.94	5 836 526		0.84
$FUAPI_{Florence}$		**0.63 (level 2)**						
Genoa	01.1	241	162 973	36 599	1.00	4 633 119	6 958 445	0.67
	01.2	51 770			0.68	6 829 103		0.98
	01.3	23 571			0.86	6 918 500		0.99
	01.4	4 341			0.97	6 016 318		0.86
	01.5	3 841			0.98	6 877 046		0.99
$FUAPI_{Genoa}$		**0.80 (level 1)**						
Milan	01.1	1 111	101 507	75 817	0.99	5 623 252	6 958 432	0.81
	01.2	14 596			0.86	4 694 074		0.67
	01.3	18 868			0.81	6 403 418		0.92
	01.4	7 772			0.92	6 492 690		0.93
	01.5	1 307			0.99	6 317 461		0.91
$FUAPI_{Milan}$		**0.78 (level 2)**						
Naples	01.1	148	117 821	54 726	1.00	5 422 923	6 925 684	0.78
	01.2	46 102			0.61	6 470 575		0.93
	01.3	13 976			0.88	6 239 064		0.90
	01.4	1 015			0.99	4 501 961		0.65
	01.5	2 156			0.98	6 583 886		0.95

(*continued*)

Table 4. (*continued*)

City	ID FUA_i class	Pop. of FUA_i	Pop. of spatial proximity	Stadium capacity	w_i	Cluster area of KDE [m^2]	Spatial proximity [m^2]	k_i
$FUAPI_{Naples}$		**0.74 (level 2)**						
Palermo	01.1	432	47 194	36365	0.99	3 709 653	6 933 679	0.54
	01.2	28 089			0.40	4 429 551		0.64
	01.3	11 470			0.76	4 769 843		0.69
	01.4	3 147			0.93	4 598 927		0.66
	01.5	706			0.99	5 776 911		0.83
$FUAPI_{Palermo}$		**0.55 (level 2)**						
Rome	01.1	328	33 957	72 698	0.99	5 018 614	6 944 412	0.72
	01.2	12 721			0.63	4 793 259		0.69
	01.3	12 222			0.64	6 309 382		0.91
	01.4	7 334			0.78	5 931 941		0.85
	01.5	511			0.98	6 944 412		1.00
$FUAPI_{Rome}$		**0.68 (level 2)**						
Turin	01.1	5	85 980	41 507	1.00	5 517 422	6 956 493	0.79
	01.2	7 272			0.92	5 971 570		0.86
	01.3	10 859			0.87	6 458 354		0.93
	01.4	6 571			0.92	6 187 469		0.89
	01.5	8 390			0.90	6 956 493		1.00
$FUAPI_{Turin}$		**0.82 (level 1)**						
Verona	01.1	637	75 095	39 211	0.99	5 690 633	6 954 391	0.82
	01.2	17 980			0.76	6 289 915		0.90

(*continued*)

Table 4. (*continued*)

City	ID FUA_i class	Pop. of FUA_i	Pop. of spatial proximity	Stadium capacity	w_i	Cluster area of KDE [m^2]	Spatial proximity [m^2]	k_i
	01.3	5 854			0.92	6 635 021		0.95
	01.4	994			0.99	5 336 743		0.77
	01.5	3 294			0.96	6 921 891		1.00
$FUAPI_{Verona}$		**0.82 (level 1)**						

Table 5. Summary results and Policy.

City	Carry Capacity (CC) [%]	FUAPI [0-1]	FUAPI level scenario	Policy
Genoa	78	0.80	1	Soft policy TPL
Naples	54	0.74	2	Soft policy TPL
Turin	52	0.82	1	Soft policy TPL
Verona	48	0.82	1	Soft policy TPL
Florence	28	0.63	2	Hard/soft policy TPL
Bologna	26	0.68	2	Hard/soft policy TPL
Milan	25	0.78	2	Hard/soft policy TPL
Palermo	23	0.55	2	Hard/soft policy TPL
Cagliari	-	0.70	2	Hard policy di TPL
Rome	-	0.68	2	Strong policy di TPL
Bari	-	0.48	3	Exclusion

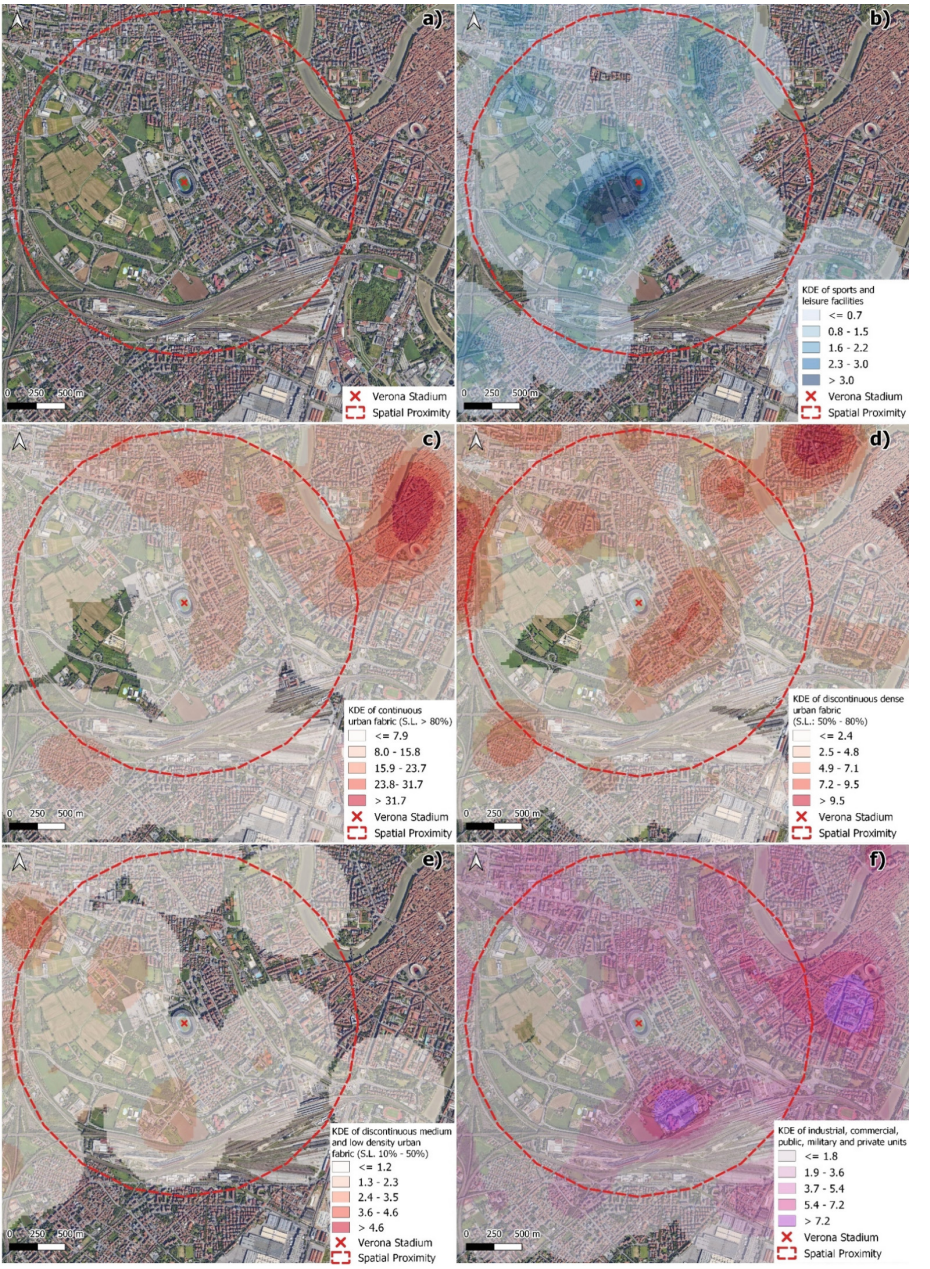

Fig. 4. Verona - Kernel Density Estimation and spatial proximity (Author: Sinatra M., 2024).

The analysis performed provides policy suggestions (Table 5) based on the scores gained by the different cities considered in terms of the FUAPI index and Carry Capacity. Cities like Genoa, Naples, Turin and Verona do not need important public transport policies, due to their configuration in terms of the sport facilities and level of services. More relevant interventions are needed in Florence, Bologna, Milan and Palermo, while the bottom of the table host Cagliari and Rome, that need harder policies, but still realizable. Bari, given its score, would be excluded from the selection.

6 Conclusion and Future Development

The present research was aimed at developing the FUAPI Index, based on an interdisciplinary approach, combining the 15-min city paradigm, the spatial distribution of the population and the concentration of urban functions.

As discussed previously, the focus in this document was on the area near the candidate Italian cities to host the European Football Championship 2032, assuming a buffer zone of approximately 15 min (radius 1,500 m) around the reference stadium and superimposing the density of residences and of urban services. This was achieved using various spatial analysis techniques, Kernel density in particular. A minimum unit of 25 m was used to collect and represent the results. The objective of future research is to continue in this line, using the Triple Access Planning (TAP) dataset, which is based on urban accessibility, which can be achieved through the transport system (physical mobility), the territorial system (spatial proximity) and the telecommunications system (digital connectivity). Digital connectivity, i.e. being connected, has in fact become an integral part of daily life, as important for communities and businesses as connection to service networks and therefore relevant in urban planning.

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Critical Interpretation of SDGs Strategies at Regional Scale: Are There More Important Goals for Italy?

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Abstract. The significance of the Sustainable Development Goals (SDGs) extends not only to the global context but also to the national and regional sphere. Universally adopted by all United Nations Member States in 2015 as a collective call to action to eradicate poverty, safeguard the planet, and ensure prosperity for all, the SDGs offer a comprehensive roadmap for addressing the world's most pressing challenges. Recognizing the interconnected nature of social, economic, and environmental issues, the SDGs underscore the necessity of a holistic and integrated approach to development.

The implementation of the 2030 Agenda at various territorial levels involves the utilization of National Sustainable Development Strategies and Regional Sustainable Development Strategies. Voluntary reviews reveal the formidable challenge of reaching the lower levels of the territorial chain. The absence of specific goals in regional strategies and a lack of economic investments can lead to the erosion of the holistic vision embedded in the 2030 Agenda.

In this synthetic framework, the objective of the paper is to develop a methodological approach to compare the Regional Strategy for Sustainable Development (RSSD) with Regional Competitiveness Index (RCI).

The findings offer a stimulating basis for assessing the correlation in the Italian regions between RSSD and a set of sub-indices of RCI of basic, efficiency and innovation.

Keywords: Holistic vision · Sustainability · Planning for future

1 Introduction

The significance of Sustainable Development Goals (SDGs) cannot be overstated in the global context but also in the local one. Adopted by all United Nations Member States in 2015 as a universal call to action to end poverty, protect the planet, and ensure

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prosperity for all, the SDGs represent a comprehensive roadmap for addressing the world's most pressing challenges. The SDGs recognize the interconnectedness of social, economic, and environmental issues, emphasizing the need for a holistic and integrated approach to development. The goals not only outline a vision for a more equitable and sustainable world but also provide a common language and set of targets and measures for governments, businesses, and communities to work collaboratively towards a shared future.

The implementation of the 2030 Agenda at the national level has gone through National Sustainable Development Strategies (NSDS) and Regional Strategies for Sustainable Development (RSSD) [1]. Each State has participated in defining the indicators for measuring the SDGs and has appointed official bodies for monitoring, such as UNSTAT, EUROSTAT for the EU, and national statistical agencies for individual EU member states (e.g., ISTAT for Italy), as mandated in the EU communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Next steps for a sustainable European future, European action for sustainability in 2016 [2].

We are currently in a phase where voluntary reviews are conducted to adjust the trajectories of individual States or Regions in relation to the common goals of the 2030 Agenda. Voluntary reviews demonstrate how challenging it is to reach the lower levels of the territorial chain (provincial and municipal level), with the exception of capital cities [3].

The EU has reviewed its alignment with UN Goals and set up several data platforms and indicators to bolster community policies. These platforms aid in analysing the consistency between agendas adopted by different member states and community policies. Measurement platforms are also in place for comparing progress among EU regions and member states, with ongoing reviews aimed at enhancing the measurement of progress towards the SDGs within the EU context [4].

Within this wealth, but also complexity of information, the need for a clear measurement of the effects of national choices within the community context and vice versa is evident. These platforms can also prove useful for internal reflections within States, enabling the comparison of regions by simultaneously examining both policies related to the implementation of the 2030 Agenda at the local level (RSSD) and indicators of the economic context in which programmatic choices are made. Moreover, almost five years from 2030 and midway through the targets for 2050, and a decade after the approval of the ONU 2030 Agenda, numerous unexpected disruptive elements have emerged concerning the goals: the COVID-19 pandemic, wars, even in Europe, and the increasing number of natural disasters linked to climate change.

Although the debate on the implementation of the 2030 Agenda in academic circles is rich, in most cases, it is focused on the vertical interpretation of individual goals, thus losing sight of the holistic vision of the 2030 Agenda, which aims for a balance of policies based on territorial specificity. A brief literature review conducted using the keywords "Agenda 2030," "SDGs," and "policy" in the Scopus database for the last five years (2019–2024) yields 179 records. However, only 65 of these records can be deemed comprehensive and aligned with the holistic vision outlined in the 2030 Agenda. Conversely, the remaining records are predominantly focused on individual

goals or specific target issues, such as tourism, gender, health, energy, agriculture, and water. This suggests that a limited number of scholars are actively engaging with the interdisciplinary values envisaged in Agenda 2030, hindering their potential contribution to supporting the development of public policies. Embracing this interdisciplinary vision is crucial for bridging the research gap between theoretical and applied studies.

Furthermore, in this corpus, 24 papers deliver critical assessments, strategic methodologies, and policy perspectives at multilevel scales (Table 1). Among them 6 papers showcase policy and case studies beyond Europe, while 8 focus specifically on European countries. Additionally, only 10 papers delve into broader strategic perspectives on the 2030 Agenda and its impacts.

Table 1. Paper selected with critical reviews, strategic approaches, and policy perspectives at multilevel scales on holistic 2030 Agenda vision.

Publication Title	Year	Source
Analysis of the coverage and discourse of the Sustainable Development Goals and the 2030 Agenda in the Spanish digital press (2015–2022)	2024	[5]
Engaging the United Nations' Agenda 2030 in strategic governance of "Europe's most sustainable city"	2024	[6]
From global goal to local development policy: How partnerships as a policy idea changes through policy translation	2023	[7]
Localizing the sustainable development goals: A multivariate analysis of Spanish regions	2023	[8]
Urban Policies in the Framework of the 2030 Agenda: The Case of Bristol, England	2023	[9]
Agenda 2030: systemic interrelationships between the Sustainable Development Goals	2022	[10]
Can Agenda 2030 bring about "localization"? Policy limitations of Agenda 2030 in the broader global governance system	2022	[11]
Curriculum and the United Nations' sustainable development goals	2022	[12]
Implementing Water-Energy-Land-Food-Climate Nexus Approach to Achieve the Sustainable Development Goals in Greece: Indicators and Policy Recommendations	2022	[13]
SDG interlinkage networks: Analysis, robustness, sensitivities, and hierarchies	2022	[14]
SDGs Implementation in Italy: A Comparative Assessment of Subnational Strategies for Sustainable Development	2022	[15]
Sustainable Development Goals (SDGs): assessment of implementation progress in BRICS and MINT	2022	[16]
Sustainable Development Goals and Sustainability Governance: Norms, Implementation Pathways and Caribbean Small Island Developing States	2022	[17]

(*continued*)

Table 1. (*continued*)

Publication Title	Year	Source
Territorializing and Monitoring of Sustainable Development Goals in Italy: An Overview	2022	[18]
The Territorialization of the 2030 Agenda and the Evolving Policy Framework for Sustainable Development in Italy. The Case of the Metropolitan City of Turin	2022	[19]
Achieving Sustainable Development Goals of Agenda 2030 in Bangladesh: the crossroad of the governance and performance	2021	[20]
Analyzing the contributions of transdisciplinary research to the global sustainability agenda in African cities	2021	[21]
Bringing the Global to the Local: the challenges of multi-level governance for global policy implementation in Africa	2021	[22]
Pathways, contextual and cross-scale dynamics of science-policy-society interactions in transdisciplinary research in African cities	2021	[23]
Policy coherence across Agenda 2030 and the Sustainable Development Goals: Lessons from Finland	2021	[24]
Beyond Agenda 2030: Future-oriented mechanisms in localising the Sustainable Development Goals (SDGs)	2020	[25]
Getting to 2030 - Scaling effort to ambition through a narrative model of the SDGs	2020	[26]
How is progress towards the Sustainable Development Goals measured? Comparing four approaches for the EU	2020	[27]
Insights on the United Nations Sustainable Development Goals scope: Are they aligned with a 'strong' sustainable development?	2020	[28]

The paper acknowledges the importance and opportunity of having numerous comparison and analysis tools proposed by the EU and attempts to apply them. For the Italian case study, it proposes an integrated analysis that combines the significance given by individual Regional Strategy for Sustainable Development (RSSD) to the Goals of the 2030 Agenda and European context indicators at the regional economic level. This analysis investigates towards which SDGs the regions intend to invest and identifies the sectors that are driving investments in the regions. Understand the links between territorial economies and the objectives outlined in the RSSDs, determining whether regional strategies must necessarily be supported by incentivizing mechanisms at the national/community level for effective implementation.

The manuscript is two sections: Comparison between EU Regional Competitiveness Index factors and SDGs indicators at regional scale (Sect. 2) and Critical interpretation (Sect. 3).

2 Comparison Between EU Regional Competitiveness Index Factors and SDGs Indicators at Regional Scale

The European tools used for the comparative reading are:

- SDG Mapper[1]
- Regional Competitiveness Index (RCI)[2] interactive tool.

The SDG Mapper, found on the *KnowSDGs* platform, is a web-based application based of Joint Research Center (JRC) studies [29–38] that provides tools and organizes knowledge on policies, indicators, methods and data to support the evidence-based implementation of the SDGs by enabling users to dynamically map any document against the SDGs at both goal and target levels. Utilizing a keyword approach, the tool offers a robust method for pinpointing specific topics related to the SDGs within the text [39]. The primary goal of the SDG Mapper is to assist users in contextualizing their work within the framework of the SDGs. By doing so, it aims to enhance comprehension of the 2030 Agenda, including its Goals, targets, and indicators. The ultimate objective of the SDG Mapper is to streamline the integration of the SDGs into various policy and decision-making processes. The mapping tool presents diverse data visualizations and furnishes information on the indicators underlying the identified goals and targets. Additionally, it features an SDG reference tracker that enumerates direct references to the 2030 Agenda discovered in the uploaded documents. The application of the automated SDG mapping approach [37] to map RSSD onto the SDGs can contribute significantly to better incorporating the 2030 Agenda into the regional policy landscape.

Results of the mapping process can be downloaded for further comprehensive data analysis and interpretation.

In this paper the interpretation is done using also Regional Competitiveness Index (RCI). The definition of the RCI framework slightly differs from the national framework [40, 41] as it incorporates the perspectives of both businesses and residents [42]. According to this definition, regional competitiveness is defined as the ability of a region to provide an attractive and sustainable environment for firms and residents to live and work. This definition seeks to balance the objectives of business success with those of societal well-being, contributing, at least partially, to the ongoing 'beyond GDP' discussion. Sustainability in this context refers to a region's capacity to offer an appealing environment in both the short and long term [43].

Drawing inspiration from the World Economic Forum's (WEF) framework for the Global Competitiveness Index (GCI), the RCI adapts and extends this framework to the regional context within the EU. The aim is to capture the underlying factors that support a region's long-term economic development. The RCI comprises three sub-indices [43]:

- 'Basic' (fundamental drivers applicable to all types of economies),
- 'Efficiency' (a skilled labour force and a more efficient labour market), and
- 'Innovation' (drivers of improvement at the most advanced stage of economic development).

[1] https://knowsdgs.jrc.ec.europa.eu/sdgmapper.

[2] https://ec.europa.eu/regional_policy/assets/regional-competitiveness/index.html.

These sub-indices are further articulated into 11 pillars, each describing different aspects of competitiveness. According to Dijkstra et al. (2023) in this paper, the pillar highlights include *Institutions, Labour market,* and *Technological* readiness (Fig. 1) [43].

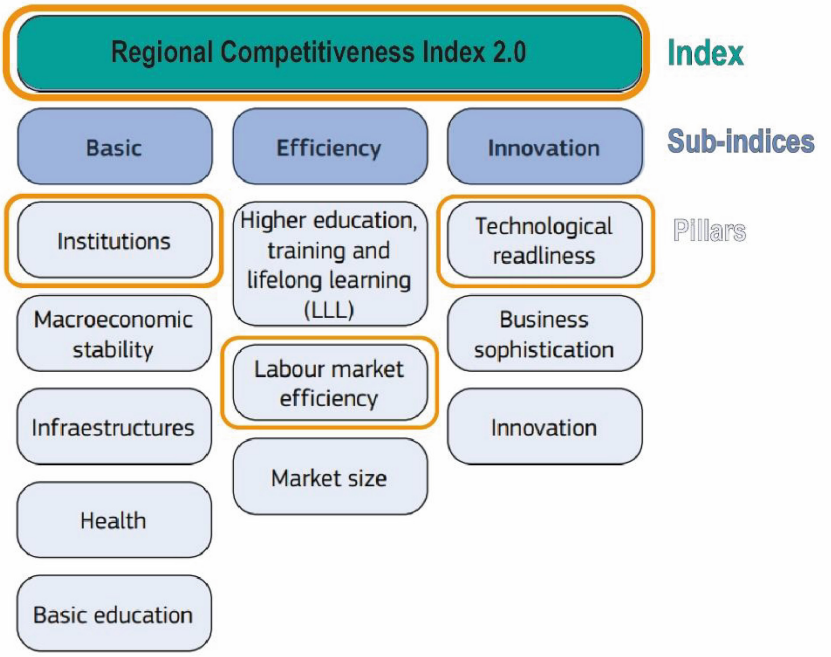

Fig. 1. RCI 2.0 framework structure [43]. The pillars used in the paper in orange.

The 'Institutions' pillar assesses the quality and efficiency of institutions, the perceived level of corruption, and the general regulatory framework within countries. It gauges the extent to which people trust their national legislative and regulatory systems, along with managers' perceptions of the efficiency and reliability of various aspects of the business environment. The 'Labour Market' pillar provides a crucial indicator of a region's economic development. Efficient and flexible labour markets contribute to the effective allocation of resources. The 'Technological readiness' pillar measures the extent to which households and enterprises are using and adopting existing technologies. The adoption and diffusion of new technologies are widely recognized as fundamental to boosting growth and competitiveness [43]. These three pillars assist researchers in identifying the obstacles that the regional sustainable development strategy may face in its specific context, thereby revealing potential constraints on its implementation. It is widely recognized that executing a strategy is not solely the duty of the public sector; instead, it heavily depends on active involvement from the private sector and businesses. The 'Institutions' pillar not only forms the regulatory framework for potential investments but also assesses the institutional climate, indicating whether it's supportive or

not. Assessing 'Labour Market efficiency' in economic development allows us to gain insight into the types of investments best suited for that territory. Similarly, evaluating 'Technological readiness' helps us determine whether the reference context is dynamic enough to effectively utilize innovative technologies.

A deeper understanding of the interplay between regional policies and the 2030 Agenda, encompassing its 17 goals and 169 targets, can enhance policy coherence for sustainable development. This involves reinforcing local capacity to formulate, execute, and monitor cohesive and integrated policies for sustainable development. Effectively implementing the SDGs through a coherent set of actions presents a challenge for regional governments.

The integrated framework is organized into three tables, facilitating a comparative analysis of the impact of the 17 Goals in the RSSD among regions within the same relative range of the RCI. In each table, the left side presents the thematic map of the RCI with bar graphs depicting the reference regions for the three pillars: *Institutions, Labour market,* and *Technological readiness.* On the right side, a bar graph is provided for each region, illustrating the incidence of the SDGs in the RSSD.

Across all of Italy, excluding the Lombardy region, the RCI is below the European average (EU-27, which is set at 100 points). The **first chart** (Fig. 2) represents the Southern regions of Italy and the islands, which have an RCI ranging from 50 to 75 points, the lowest in the country and comparable to other EU regions such as Greece, Romania, Bulgaria, Hungary, Andalusia, and Extremadura (Spain). Additionally, these regions are considered less developed in terms of GDP. All the strategies of these regions focus on Goal 11, while attention to Goal 17 does not seem to be recurrent. It is noteworthy that 'institutions' consistently score below 50 in the respective pillar of the RCI. Both Campania and Sardinia are predominantly focused on Goal 11, each reaching over 20% of citations, despite weaknesses in both institutional aspects and the labour market for the former and greater dynamism for the latter. Puglia, Sicily, and Molise, despite their differences, maintain a more varied distribution among the SDGs. Puglia exceptionally emphasizes Goal 6, likely linked to the attention given to the Puglian aqueduct, and Goal 15. Sicily, on the other hand, focuses on Goals 7 and 8, presumably related to renewable energy, but within a weak 'labour market' context and relatively strong 'technological readiness'. Finally, Molise concentrates on Goal 13, addressing climate change, supported by a sufficiently strong 'labour market'. The strategies of Calabria and Basilicata are still being defined and therefore cannot be evaluated.

The **second chart** (Fig. 3) represents regions with an RCI ranging from 75 to 90 points, consistently below the EU average. In terms of GDP, Abruzzo, Molise, and Marche are considered in transition, while the other regions in the area are deemed developed. All the strategies of these regions focus on Goal 11, with a strengthening of interest in Goals 8, 15, and 13. Additionally, Liguria and Tuscany also show interest in Goal 10. In comparison to less developed regions (Table 1), scores for institutions and the labour market are significantly higher, except for Abruzzo. The labour market indices of Bolzano and Valle d'Aosta align with the EU average.

The **third chart** (Fig. 4) represents regions with an RCI ranging from 90 to 110 points, indicating proximity to the EU average and a higher level of development in terms of GDP. Lombardy is the only region with an RCI above the EU average (EU-27 = 100), similar to regions such as Costa Azzurra, Brittany, and Estonia. The strategies of these regions focus not only on Goals 11, 12, 13, and 8 but also on Goals 3, 4, and 15 (except for Veneto). All regions have a high 'labour market' score around 90 points (except for Lazio). Trento, as a special statute province and equivalent to a region, has stronger 'institutions', and the 'technological readiness' is around 70 points.

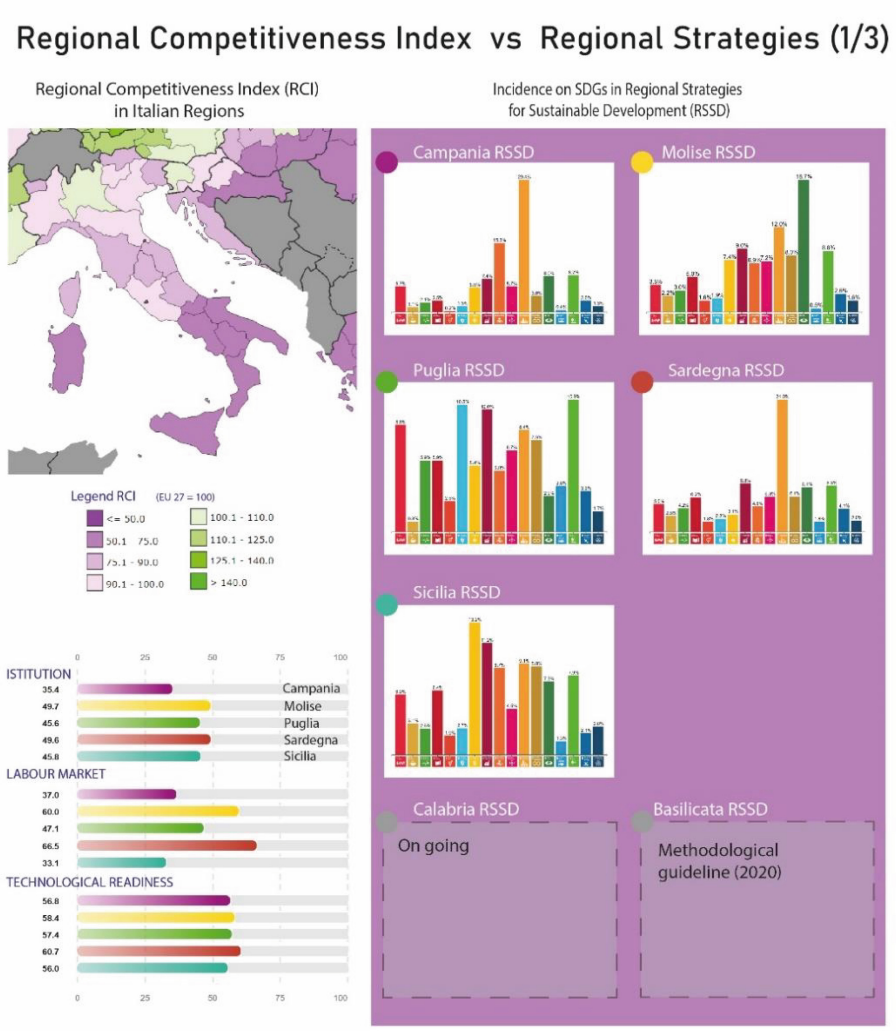

Fig. 2. The chart1 shows the impact of the 17 Goals in the Regional Strategy for Sustainable Development (RSSD) within the same relative range of the Regional Competitiveness Index (RCI) (50–75) among Italian regions.

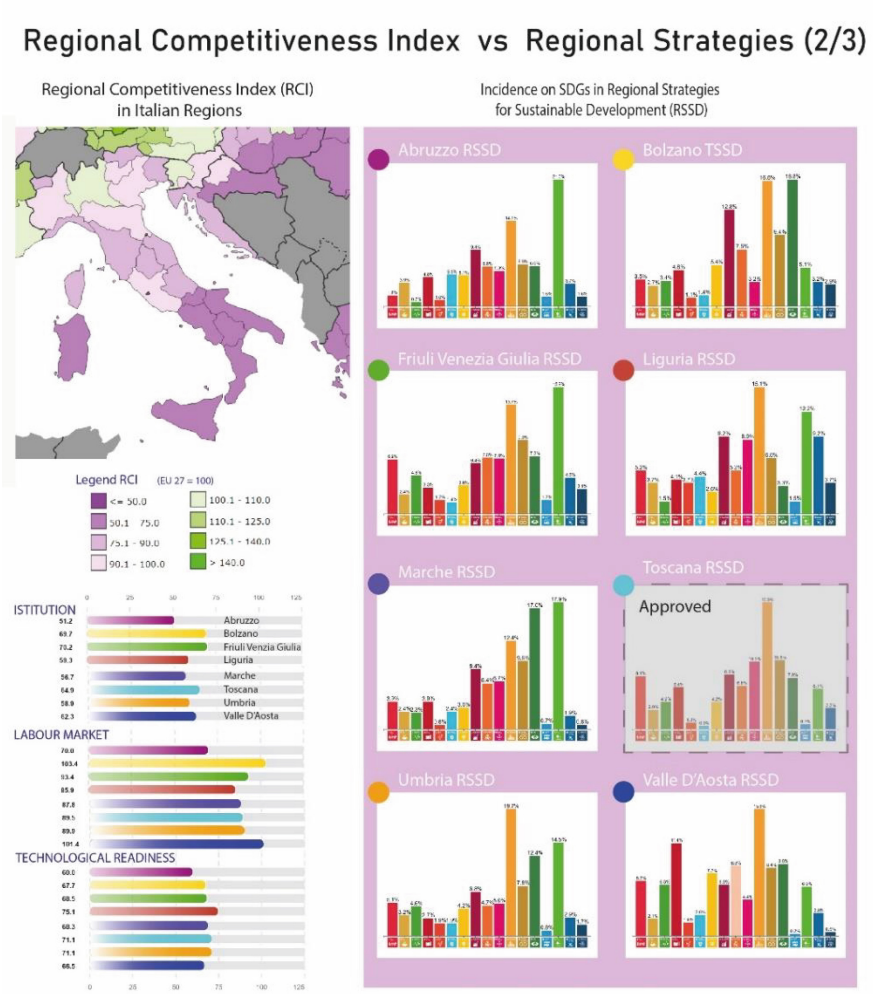

Fig. 3. The chart 2 shows the impact of the 17 Goals in the Regional Strategy for Sustainable Development (RSSD) within the same relative range of the Regional Competitiveness Index (RCI) (75–90) among Italian regions.

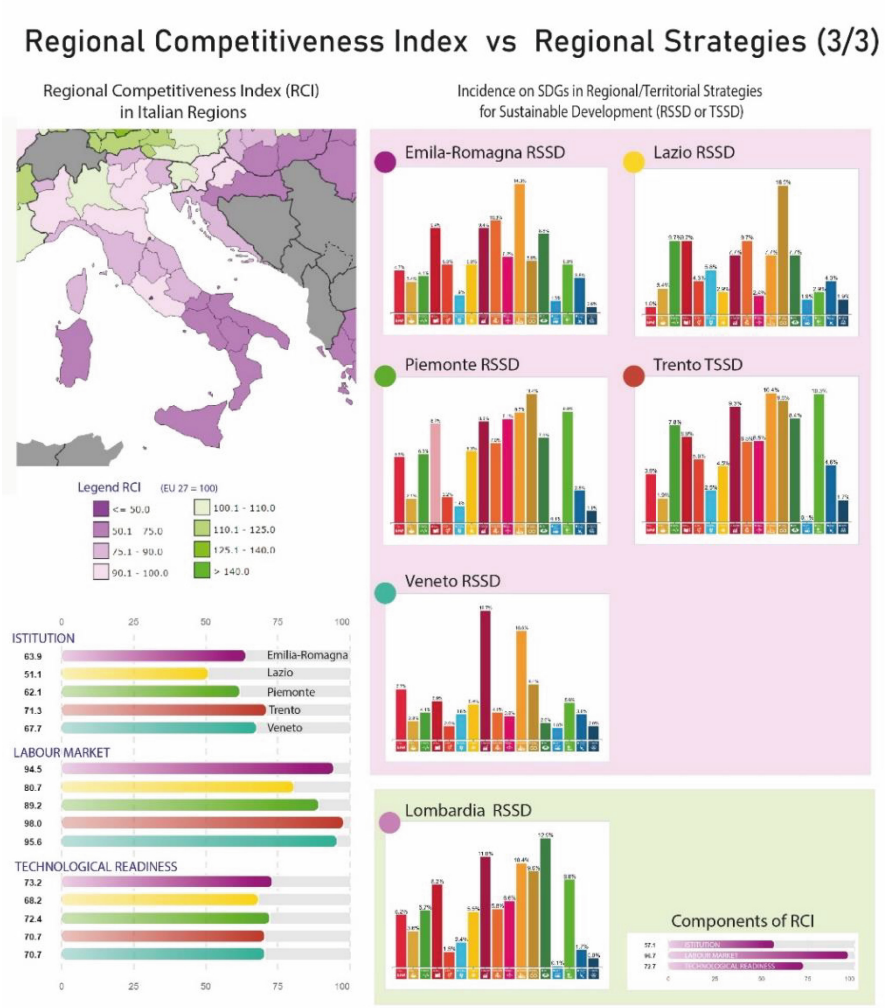

Fig. 4. The chart 3 shows the impact of the 17 Goals in the Regional Strategy for Sustainable Development (RSSD) within the same relative range of the Regional Competitiveness Index (RCI) (90–110) among Italian regions.

3 Critical Interpretation

The present research confirms that "more developed regions (with a GDP per head above 100% of the EU average) perform better than transition (between 75% and 100%) and less developed regions (with a GDP per head of less than 75%) in all components of the RCI" [43].

The RSSDs in less developed regions prioritize the urban dimension, whereas transition regions place greater emphasis on goals associated with environmental themes like climate change, life on land, and water, culminating in production. Additionally,

transitioning regions exhibit a heightened interest in the quality of life influenced by the production system, well-being, and education. Overall, RSSDs consistently assume a marginal role with respect to Goals 16 and 17, affirming the barrier underscored by Widuto in 2022 at the European Parliament Think Tank [44].

The primary obstacles to achieving SDGs at the local level are not jet overcome and they regard a discontinuity in political dedication to sustainable development, insufficient awareness, a lack of coordination across various governance levels and policy departments [45], limited financial resources, and a deficiency in the capacity to track indicators and establish connections among the diverse indicator systems maintained by the UN, Eurostat, as well as national and regional authorities.

The delay in attaining the targets set forth in the 2030 Agenda poses a threat to national competitiveness. The economic repercussions of the postponed policies directed towards the objectives of the 2030 Agenda have not been assessed by the regions yet. Nevertheless, the price of indecision can lead to a decline in competitiveness for the territories and can hinder technological readiness and the evolution of the labour market [46].

Therefore, we need an effort in maximizing synergies and navigating trade-offs across various policy areas; fostering vertical and horizontal cooperation among all levels of governance, including public administrations and other relevant stakeholders; engaging Local and Regional Authorities (LRAs) in the formulation of national strategies; formulating indicators pertinent to the local level; and consulting LRAs to tailor indicators to address local issues and tasks [44].

Similarly to the EU's approach in the 2023 Voluntary Review [19], which examined internal and external relations within the EU, it is advisable to observe the internal and external relations of individual regions. The National Voluntary Review (NVR) and Local Voluntary Review (LVR) of regions should concentrate on strengthening governance, particularly the implementation of SDGs 16 and 17. Achieving this goal requires a heightened awareness of the internal and external implementation of RSSD, encompassing policy coherence and spillover effects. Regions communicate the Agenda's objectives through RSSD, and these objectives should be implemented using territorial and sectoral planning instruments.

The links between local policies and economies and the objectives included in the regional strategy for sustainable development are both multiple and complex. The key points of this connection are based on inclusive and sustainable economic growth that benefits communities, without depleting natural resources. Innovation, economic diversification, and the valorisation of local resources constitute both opportunities and challenges. In fact, local economies are often directly dependent on the natural resources of the area (agriculture, fishing, tourism, etc.). Sustainable development strategies must include the conservation of resources, sustainable management, and the reduction of impacts on the climate and the environment to guarantee renewed spatial justice (Goal 16). In this sense, social equity and territorial cohesion through access to services, education, healthcare and energy, strengthen local economies, which together with innovation and new skills can stimulate the creation of new jobs, businesses and local economic sectors, while offering solutions to climate and environmental challenges within the framework of multilevel governance (Goal 17).

The support incentives within the RSSD to stimulate sustainable practices in businesses, communities and public bodies must be integrated on multiple fronts to be effective: financial incentives, community training and involvement, green public procurement and circular economy, innovation, and research. In this sense, the indicators (environmental, economic, social and governance) allow us to evaluate to what extent the integrated action of incentives can contribute to the achievement of sustainable development objectives, offering a basis for remodulation and reporting. For monitoring, the indicators must be specific, measurable, achievable, relevant, and timely (SMART) and therefore reliable in decision-making processes and performance evaluation.

To enhance coherence between commitments and government actions, a driving force could be provided by the Strategic Environmental Assessment (SEA) and Environmental Impact Assessment (EIA) [47].

The use of SEA/EIA, incorporating monitoring indicators from the 2030Agenda, would help ensure a proper understanding of the trajectories of strategic choices made by regions, particularly regarding the interconnection between SDGs.

As emphasized by the Intergovernmental Panel on Climate Change (IPCC) [48, 49], there are indeed various possible scenarios to implement the necessary transitions to fulfil the 2030Agenda. Local authorities must adopt the cultural dimension of the SDGs. This implies that the 2030Agenda should become a way of shaping policies and regulatory acts [50]. In line with the commitment to balance SDGs, as embedded in the ethos of 2030Agenda, it is important to explore the possibility of reassessing the internal structure of local authorities, giving substantial attention to the current connection between sustainability and innovation [51].

In this sense, the gap found (chart 1, 2 and 3) of the three macro regions: north, centre and south which confirms what theorized by Hans Singer [52, 53], through the distinction between "centre" and "periphery" to explain how the economic and social inequalities between and within nations. According to Wallerstein I. [54, 55] and adapting the global model also to individual nations, northern Italy could be associated with the centre, central Italy with the semi-periphery and the south with the periphery [56].

Despite its limitations, centre-periphery theory remains fundamental to understanding power dynamics and spatial inequalities. It offers a framework for analysing how economic policies and therefore incentives can influence the development of countries and regions, highlighting the need for more balanced and sustainable strategies to promote inclusive development.

Future perspectives for this research could involve analysing RSSDs trends based on voluntary revisions that regions will undertake in the future to understand the evolution of the strategies over time. Additionally, the research could be extended to other subregional territorial levels of investigation (such as provinces, homogeneous territorial areas, or municipalities). To broaden the perspective, it could be beneficial to compare the link between regional strategies with other synthetic performance indices of environmental or social nature and also governance, in order to holistically complete the quadruple bottom line model of sustainability [57].

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A.R.; writing - original draft preparation M.P, A.R.; writing - review and editing A.R., M.P G.B.; supervision G.B. All authors have read and agreed to the published version of the manuscript.

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Graph Neural Networks for Metrics Prediction in Microservice Architecture

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Abstract. The article examines the issues of monitoring performance in microservice architectures. We explore the problem of forecasting performance indicators as well as fault propagation in such systems, which are distributed and have independent service deployments. The paper addresses these issues by proposing a novel approach that uses multimetric time series data to establish causal relationships between microservices and build graph neural networks based on revealed system dependencies. The method's goal is to proactively forecast performance indicators and fault propagation in order to assure the resilience and reliability of microservices. Various graph neural network architectures are discussed. The best one DCRNN uses a diffusion convolutional recurrent neural network in a basis and is able to predict well both on data with and without anomalies.

Keywords: Graph neural networks · Microservice · Metrics prediction · microservice preformance

1 Introduction

The shift towards microservice architectures in software development has become widespread, dividing monolithic architectural parts into smaller interconnected elements. This approach is used for various software solutions, including cloud-based applications. Microservices-based applications can be implemented by various service providers using various technologies or programming languages in multiparty and open network environments [5,24].

However, in contrast to a monolithic application, there is a need to handle service-to-service communication resulting from the dispersion of the system's different components. The reason for this is that every service in a microservice architecture is deployed independently and requires intercommunication with one another. This could lead to problems including latency, inconsistent data, and network errors. At their turn, failures may threaten the reliability of the system due to the unclear responsibility of multiple internal microservices for the fault, thus introducing challenges in monitoring and maintaining system performance.

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The key difficulties concerning microservices performance monitoring are recognized and thoroughly covered in the literature. They include isolating the root cause of system faults [6,20,23], detecting anomalies [4,10,14], and predicting performance [13,25]. Performance is typically measured using a number of metrics (throughput, response time, error rate, resource usage, etc.) that hint at various potential system issues. For instance, throughput refers to the number of requests processed by a microservice within a given time frame (usually a second: QPS). It indicates the system's capacity to handle a certain load and is essential for determining the overall system efficiency. Resource utilization metrics, such as CPU utilization, memory usage, and network bandwidth, provide insights into how efficiently resources are being utilized by a microservice and help to optimize resource allocation. The error rate measures the frequency of errors encountered by a microservice during its operation. Monitoring error rates helps identify issues impacting service reliability and the user experience.

The dynamic behavior of microservices, with their distributed and interconnected nature, makes traditional monitoring approaches insufficient for handling the intricacies of these systems. Predicting performance metrics and fault propagation, detecting anomalies, and localizing their root causes require more complicated methodologies that can adapt to the constantly changing nature of microservice architecture.

In this paper, we focus on the tasks of performance metrics prediction and fault propagation analysis in microservice architectures, assuming that a call graph and dependencies between microservices in the system are unknown.

To address these challenges, we develop our approach at the intersection of causality identification and neural networks. By establishing causal relationships within the microservice architecture based on multimetric time series data and constructing graph neural networks based on the reconstructed call graph, we seek to proactively anticipate performance issues, swiftly identify anomalies, and predict their propagation, which may disrupt system functionality.

To sum up, our contribution includes several points. First, we propose a way to construct microservice impact graphs using multiple types of metrics to discover causal relationships between services. The algorithm is based on the stable Peter-Clark (PC) algorithm applied to the Uniform Manifold Approximation and Projection for Dimension Reduced (UMAP) multimetric time series data. Second, we propose to apply the diffusion convolutional recurrent neural network originally developed for road traffic forecasting in order to predict performance metrics (QPS and response time 95% quantile) for the given time horizon. Third, we investigate the proposed framework trained on anomaly-free data for the network fault propagation problem.

The rest of the paper is organized as follows: we summarize the related work in Sect. 2. Section 3 presents the description of the combined model. Section 4 introduces the details of the experiment and the experimental results, Sect. 5 explains the conclusions and future work.

2 Related Work

2.1 Time Series Causal Discovery

Time series causal discovery involves identifying causal relationships and dependencies between variables in time series data. There are several classes of methods that can be employed to uncover causal links and understand the temporal dynamics of systems. We briefly describe the most commonly used ones in the literature applied to time series data generated by microservices metrics.

Granger Causality Test Based Methods. The most widely used causality measure is Granger causality (GC) [7,16]. It can be considered one of the basic approaches to infer causal relations from time series data, and serves as foundation for many other methods. It assesses whether past values of one variable help predict the future values of another variable. One of its potentially useful modifications is variable-lag GC [2,16], that addresses the problem of a lag between a cause and an effect being considered at a fixed time point, rather then changing in time. Methods that use transfer entropy (generalized GC) and full conditional independence [18] are based on mutual information calculation and are rather computationally expensive and suffer from the curse of dimensionality.

Causal Network Learning Algorithms. There are two basic methods for learning a directed acyclic graph (DAG): score-based and constraint-based approaches. Constrained-based approaches, such as Peter-Clark (PC) [8,22] and Fast Causal Inference (FCI) [21], learn the causal graph's skeleton via conditional independence tests before orienting the edges according to established orientation constraints. Score-based approaches, such as Greedy Equivalence Search (GES) [9], assign scores to various causal graphs using a specified score function and then search the space of DAGs for the best one.

Structural Equation Models. These methods aim to construct a model based on linear and non-Gaussian assumptions and solve it to get graph [9]. Among structural equation-based methods, Linear Non-Gaussian Acyclic Model (LiNGAM) [19] can be considered to be a baseline approach, however it is linear, assumes that there are no unobserved confounders and may not converge to a correct solution if the initial state is badly chosen. To improve LiNGAM estimation, for example, Fast Adjacency Skewness (FASK) [17] method can be used.

2.2 Time Series Forecast

Traditional Time Series Forecasting Methods. Time series prediction models, like ARMA and ARIMA, use previous values of the variables in order to predict their future values. However, accurate forecasting can be challenging when there's insufficient information about the indicator or there are complicated nonlinear dependencies between the variables [11]. In microservices domains, the multitude of service indicators and their evolving interrelationships pose such problems, so more enhanced methods should be considered for metrics prediction.

Time Series Forecasting Based on Machine Learning. Machine learning-based enhanced time series forecasting methods mostly use gradient boosting machine algorithms such as XGBoost and LightGBM, as well as recurrent neural network models such as LSTM and GRU. These models perform well with tabular data, including time series data, and are capable of capturing nonlinear relationships and interactions between variables, as well as patterns in time series data.

Spatio-Temporal Time Series Forecasting Spatial-temporal time series forecasting is a class of methods that predict future variable values based on their position and interconnection with each other. It is made up of components that learn spatial and temporal dependencies, such as graph neural networks (GNNs) for spatial relationships and recurrent neural networks (RNNs) for temporal correlations. Thus, both temporal and spatial information is stored, eliminating the need for extra temporal networks and allowing for irregular time series, varying sample frequencies, or missing data without data imputation. Based on these characteristics, they are an ideal candidate for performance metric forecasting in microservice architectures, where interconnection is critical for accurate forecasting.

3 Model

We propose a multi-variable time series prediction framework based on stable PC algorithm and graph neural network. As shown in Fig. 1, the whole algorithm is divided into the following parts:

- UMAP based metrics reduction,
- Stable PC-based causality graph construction,
- Graph neural network time series prediction.

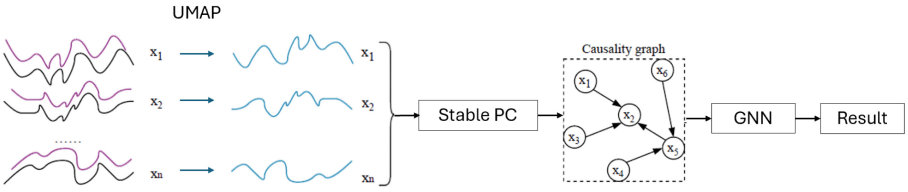

Fig. 1. The diagram of the proposed framework

The data set consists of $N \cdot m$ time series indicators collected for N microservices $(x_1, ..., x_n)$ with m performance metrics for each of them. Section 4 provides a full discussion of the data collection methods and tested description.

3.1 UMAP-Based Metrics Reduction

UMAP is a manifold learning technique for dimension reduction [1,15]. It consists of two phases: constructing a fuzzy topological representation and optimizing the low-dimensional representation to achieve the closest fuzzy topological representation as measured by cross entropy. UMAP is a k-neighbor based graph learning algorithm, with the first phase constructing a weighted k-neighbor graph and the second phase optimizing the low-dimensional representation to have the closest fuzzy topological representation. This method can create a low-dimensional representation of high-dimensional nonlinear data that retains meaningful structure and relationships, which is why it was selected for metrics reduction for the causal graph construction problem.

3.2 Stable PC Causal Graph Construction

Several algorithms were considered for causal graph construction phase: Peter Clark algorithm PC and its stable modification, LiNGAM, FCI algorithm, time-aware PC modifications (tigramite, time-aware PC) [3,18]. Stable PC algorithms [9] produce the best results in terms of the number of accurately detected connections and their directions. This is the main reason it was chosen for the framework's causality identification step.

The PC algorithm, a well-known constraint-based causal discovery method [8,22], is based on independent and identically distributed sampling with no latent confounder assumptions. It identifies conditional independencies using a search strategy and statistical methodologies. It starts with a complete undirected graph and iteratively reduces edges between conditionally independent variables to improve efficiency in sparse graphs. Edge orientations are found by detecting V-structures and using orientation propagation.

The PC-algorithm was designed for learning DAGs under the assumption of causal sufficiency, i.e., no unmeasured common causes and no selection variables. It learns a Markov equivalence class of DAGs that can be uniquely described by a so-called completed partially directed acyclic graph (CPDAG). PC algorithm starts by forming the complete undirected graph, then "thins" that graph by removing edges with zero order conditional independence relations, thins again with first order conditional independence relations, and so on. The set of variables conditioned on need only be a subset of the set of variables adjacent to one or the other of the variables conditioned.

The PC-algorithm is widely used in high-dimensional settings, since it is computationally feasible for sparse graphs with up to thousands of variables. PC-algorithm to be consistent for high-dimensional sparse graphs. Flexibility of utilizing a wide and growing class of conditional independence tests, from linear partial correlation (ParCorr) and non-parametric residual-based approaches to Kernel measures, tests based on conditional mutual information and neural networks. However, if there are unmeasured common causes or unmeasured selection variables then causal inference based on the PC-algorithm may be incorrect.

3.3 Graph Neural Networks

As we mentioned earlier, microservice systems operate in a dynamic environment that makes the problem of forecasting to require taking into account not only temporal factors in metrics data but also spatial ones related to the interconnected nature of microservices.

Moreover, the microservice metrics are influenced more by the downstream nodes than the upstream ones. This means that the spatial structure in metrics is nonEuclidean and directional.

In this research, we consider approaches based on graph neural networks applied to road traffic prediction problems, as in these tasks we encounter the same aspects as those related to microservice systems.

We investigated three recently proposed architectures: TGCN [27], STGCN [26], and DCRNN [12], which outperform the state-of-the-art approaches, and assessed their ability to make consistent predictions even when data contains faults. To the best of our knowledge, this is the first time these architectures have been used to solve a metric prediction problem in microservice architecture.

TGCN: Temporal Graph Convolutional Network. The authors integrate the graph convolutional network with the gated recurrent unit. The graph convolutional network captures the network's topological structure and models spatial dependence. The gated recurrent unit captures the dynamic changing of data to model temporal dependence.

STGCN: Spatio-Temporal Graph Convolutional Networks. To fully exploit spatial information, the authors use a whole graph representing the network structure rather than handling edges individually. For temporal dependencies prediction, they propose to use convolutional structure on the time axis rather than recurrent networks. Thus, this architecture is made up of many spatio-temporal convolutional blocks that combine graph convolutional layers and convolutional sequence learning layers to simulate spatial and temporal connections.

DCRNN: Diffusion Convolutional Recurrent Neural Network. The authors create a weighted directed network by calculating the pair-wise spatial correlations of node metrics. They describe the dynamics of interconnected node metrics as a diffusion process and suggest a diffusion convolution technique to capture spatial dependency. DCRNN combines diffusion convolution, sequence-to-sequence architecture, and scheduled sampling techniques.

4 Experiment

4.1 Experimental Setup

To locally simulate and run microservice system and collect metrics we used OpenTelemetry Demo[1]. It is an open source microservice project composed of

[1] https://opentelemetry.io/docs/demo/.

11 microservices which simulates the process of buying in on-line shop. The microservices in demo are written in different programming languages that communicate to each other over gRPC and HTTP; and a load generator which uses Locust[2] to fake user traffic. The microservice architecture is shown in Fig. 2.

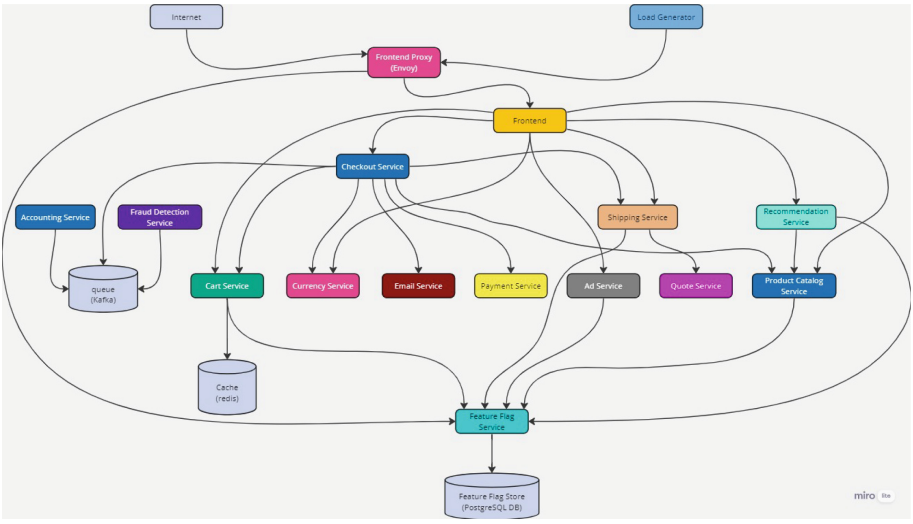

Fig. 2. Open telemetry demo microservice architecture

The traffic was injected using Locust framework. We have analyzed different shapes of users' activity on correctness of the microservice impact graph reconstruction: graduate increase of users number, graduate decrease, step-wise change of activity and '/\'-shaped profile (see Fig. 3). We had a hypothesis that stronger signal variations hesitate more microservices interconnections and it should influence the collected time-series metrics. Those ones in their turn should be better for revealing calls dependencies. '/\'-shaped profile (Fig. 3) demonstrated the best results with respect to all causality identification algorithms. That is the reason why it was used in all data acquisition scenarios.

We deploy OpenTelemetry demo application into local Kubernetes cluster with full support for a span metrics collection. These spans are processed by the Jaeger[3] microservice. Then a Prometheus microservice collects the span statics with a 15 s discreteness for QPS and response time (95% quantile) metrics. Moreover, the Prometheus microservice also collects the CPU and Memory usage statistics for each microservice directly from a Kubernetes with 60 s discreteness. To process raw collected metrics we used Grafana[4] tool.

[2] https://locust.io/.
[3] https://www.jaegertracing.io/.
[4] https://grafana.com/.

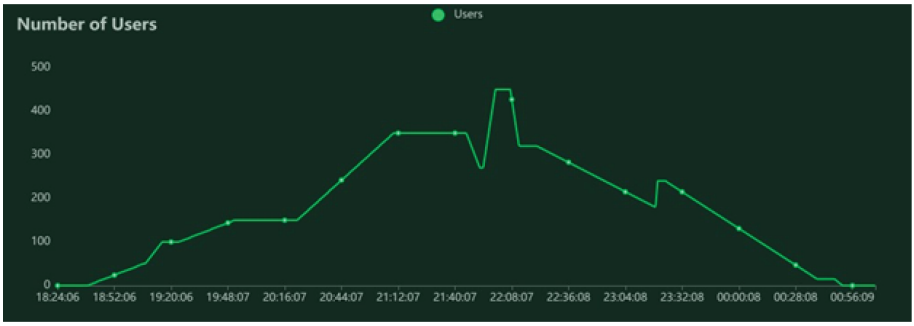

Fig. 3. Traffic injection in Open Telemetry

The profile depicted in the Fig. 3 was ran in the faultless system operation scenario. Besides it we simulated response latency faults in selected microservices in the system.

The errors were introduced into the cart, currency, and product catalog services independently and three data sets corresponding to each of the faults type were collected. Latency anomalies propagate from downstream to upstream, which is why these services were chosen for anomaly injection (see Fig. 2): they have the largest number of upstream connections, hence the number of services affected by the fault is higher.

4.2 Datasets

To assess the effectiveness of the suggested in Sect. 3 methodology, we applied the framework to a data set collected during operation of microservice system according to the described above scenario. We aimed to answer several research questions:

R1 Can graph-based neural networks predict different metrics for each of the microservices in the system, and for what time horizon? Analyze different GNNs with different time prediction parts: RNN-based, CNN-based, and diffusion-CRNN-based (described in Sect. 3).

R2 Can GNN predict faults in metrics?

R3 GNN requires system architecture in the form of an adjacency matrix. Due to the dynamic nature of the microservices, the impact graph can change with time with respect to both the nodes and edge numbers, but we can identify it with causal discovery algorithms applied to the metrics time-series data. In this case, obviously, we are able to reconstruct the graph with a certain degree of accuracy. The question is how this inaccuracy affects the quality of the prediction.

To answer the questions above, we collected four datasets in total: 1) corresponds to the normal system operation under increasing load, followed by decreasing load (the '/\'-shaped profile shown in Fig. 3); 2) response latency is

injected to the cart service (after 1800 requests to empty a cart the next 200 requests take 3 s more to execute); 3) response latency is injected to the recommendation service (after 4500 requests the next 500 requests take 1 s more to execute); 4) response latency is injected to product catalog service (after 3700 requests the next 300 requests would take 1 s more to execute).

It should be noted that time discretness of the acquired metrics is different. In order, to analyze them jointly, we considered all of them with 60 s discreteness and reduced to a single time-series for each of the microservices with UMAP method.

Thus, the training data consist of the following: for the causality identification subtask, we used a composite time series with discreteness 60 s according to the reduction procedure described above. For the prediction subtask, we used first 80% of time-series data collected during the normal operation with the user profile shown in Fig. 3 for QPS and 95% quantile time response metrics (15 s discreteness). We used 20% of the remaining normal time series data for testing purposes, along with a fault injection to the cart service, recommendation service, and product catalog service.

4.3 Results

We made several experiments with the collected data.

1. The impact graph is used from the system architecture (see Fig. 2).
2. The impact graph is constructed based on the described in Sect. 3 algorithm and UMAP algorithm.
3. The neural network is trained on the faultless data (QPS and response duration) independently and was tested on both a normal part of data and data with anomalies.

Figure 4 depicts an impact graph created using a stable PC algorithm with reduced UMAP metrics (QPS, CPU utilization, memory consumption, and response duration). The edge statistics compared to the ground truth are as follows (Fig. 2): 11 false negative edges, 8 false positive edges, and 9 true positive edges were discovered.

The Tables 1 and 2 summarize the results obtained during the first two experiments for QPS and response time 95% quantile time series data collected with 15 s discreteness.

Table 1 compares averaged metrics (MAE: mean absolute error, RMSE: root mean squared error, MAPE: mean absolute percentage error, R^2: coefficient of determination) with respect to all microservices for QPS test data. Table 2 summarizes the same values but for response time 95% quantile z-score normalized test data. The metrics were computed for three GNN-based prediction models with the assumptions that the call graph is accurately known from the system architecture and that the call graph is reconstructed using causality identification algorithms (Fig. 4). We evaluated different prediction time horizons for both cases: 3, 6, and 12 data points ahead, which correspond to 45, 90, and 180 s time horizons.

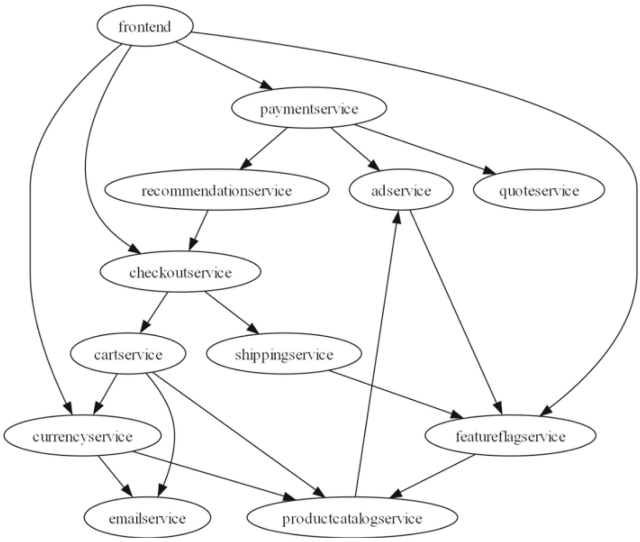

Fig. 4. Reconstructed microservices impact graph according to the model described in Sect. 3

Table 1 indicates clearly that, in both scenarios with accurate and inaccurate knowledge about the system architecture, the best results for QPS metric prediction are obtained using either TGCN or DCRNN model. However, according to the results in Table 2, TGCN failed for time response data set predictions, while DCRNN demonstrated the best metrics irrelevant to the preliminary knowledge about the system structure.

Table 1. Comparison of the results of QPS prediction using different graph neural networks architectures

Adj.	**Model**	45 sec horizon				90 sec horizon				180 sec horizon			
		MAE	RMSE	MAPE	R^2	MAE	RMSE	MAPE	R^2	MAE	RMSE	MAPE	R^2
True	**TGCN**	30.51	75.79	**43.15**	0.93	28.94	66.98	50.4	0.95	32.10	75.28	**45.27**	0.93
	STGCN	39.17	83.35	61.91	0.92	45.21	98.98	66.56	0.89	37.44	83.69	49.83	0.92
	DCRNN	**23.63**	**54.41**	45.41	**0.97**	**21.49**	**52.19**	**31.80**	**0.97**	**26.73**	**63.56**	46.41	**0.95**
Rec.	**TGCN**	27.73	63.23	**41.93**	0.95	**20.28**	**49.71**	**29.07**	**0.97**	28.67	72.35	**37.78**	0.94
	STGCN	33.99	73.83	53.55	0.94	32.82	71.74	47.55	0.94	43.34	91.94	79.27	0.90
	DCRNN	**26.78**	**58.76**	54.05	**0.96**	27.93	60.41	57.71	0.96	**27.53**	**60.71**	54.4	**0.96**

Figure 5 shows the prediction results for the frontend microservice across a 180-second time horizon using GNN-based models. The vertical line refers to the data partition between the train and test sets. These plots justify the conclusion made according to the metrics analysis. The form of QPS and time response

Table 2. Comparison of the results of response time 95% quantile prediction using different graph neural networks architectures

Adj.	Model	45 sec horizon				90 sec horizon				180 sec horizon			
		MAE	RMSE	MAPE	R^2	MAE	RMSE	MAPE	R^2	MAE	RMSE	MAPE	R^2
True	TGCN	0.99	3.13	8.92	0.94	1.10	3.60	8.90	0.93	1.49	4.51	9.06	0.88
	STGCN	2.19	6.16	10.9	0.78	2.19	6.28	11.44	0.78	2.24	6.52	11.51	0.76
	DCRNN	**0.81**	**2.41**	**7.46**	**0.97**	**0.84**	**2.83**	**7.36**	**0.95**	**0.95**	**3.33**	**7.86**	**0.94**
Rec.	TGCN	1.14	3.54	10.02	0.93	2.21	6.19	9.53	0.78	1.64	4.82	10.14	0.87
	STGCN	2.17	6.36	10.36	0.77	2.35	6.83	11.26	0.73	2.51	7.23	11.87	0.70
	DCRNN	**0.67**	**2.31**	**6.39**	**0.97**	**0.83**	**2.81**	**7.45**	**0.95**	**0.96**	**3.32**	**8.04**	**0.94**

profiles varies across microservices; we chose the frontend for illustration because it is the most representative.

The third experiment is related to the testing abilities of GNN-based models trained with faultless data to predict on data with latency anomalies in the response time and analyzing their ability to predict the metrics whose behavior is different a lot compared to the profiles during normal operation.

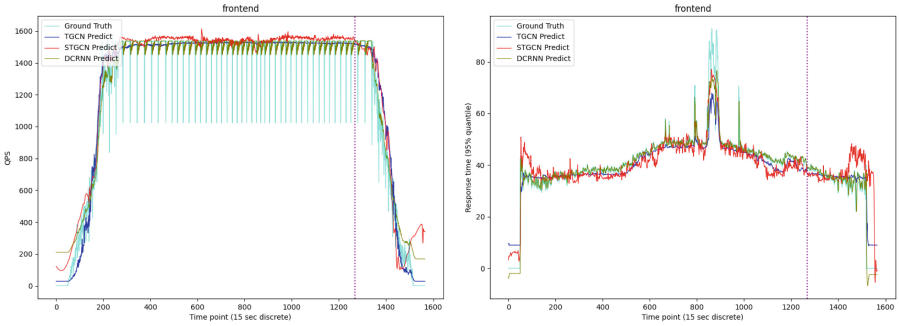

Fig. 5. Prediction for frontend over 180 s time horizon compared to the ground truth data (cyan color): left – QPS data, right – time response data. The vertical line represents the divide of data between training and testing. (Color figure online)

Figures 6 and 7 demonstrate the results of the third experiment when latency anomalies were injected into currency and product catalog service. Figure 6 depicts the RMSE values computed for all microservices QPS (left) and time response (right) test data using three evaluated GNN models with latency in the currency microservice. The color in Fig. 6 shows the spread of RMSE values within different prediction horizons (45–180 s); the straight line corresponds to the middle value (90 s). The error spread for the time response prediction is larger than for QPS, and it is natural if you take into account the time series profile shapes. The call graph was reconstructed according to the algorithm described in Sect. 3. If we compare the plots with the corresponding values from Table 1 and

2, we can conclude that DCRNN outperforms the other models with negligible degradation of error values. It is interesting because the model was trained on the data without anomalies but is still able to give good results on the faulty data.

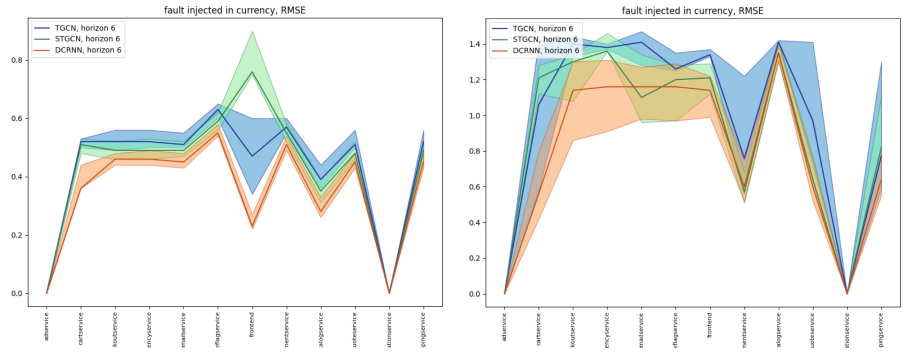

Fig. 6. RMSE values across the microservices for QPS (left) and time response (right) data with fault injected into the currency microservice. Prediction horizon is 90 s

Figure 7 compares prediction results obtained with the considered models for a randomly selected moment of time (not falling into the episode of fault occurrence) across all microservices with a 180-s prediction horizon. The charts show that the microservice where an anomaly was injected has high discrepancies between predicted and ground truth data, as do the ones that have an upstream link to the root cause microservice, for instance, frontend and checkout services (cf. Fig. 4). Thus, this observed behavior can additionally be helpful for a fault localization problem, by revealing possible root cause of the faults.

5 Conclusion

In this paper, we present our framework that integrates the stable PC method with GNN-based time series prediction model and a causality detection algorithm based on UMAP-reduced microservices metrics. As a result, it is feasible to construct links between microservices and represent them as an adjacency matrix that is fed into a GNN model. We assessed three cutting-edge systems originally developed for the road traffic prediction problem using an open telemetry demo application. Even in cases where the causation graph was reconstructed incorrectly, DCRNN produced the best results for all experiments that were examined. Including the cases when the model was trained with faultless data and tested on the data with the injected faults.

In the future, this approach will be applied to bigger data sets with an emphasis on anomaly detection and root cause investigation.

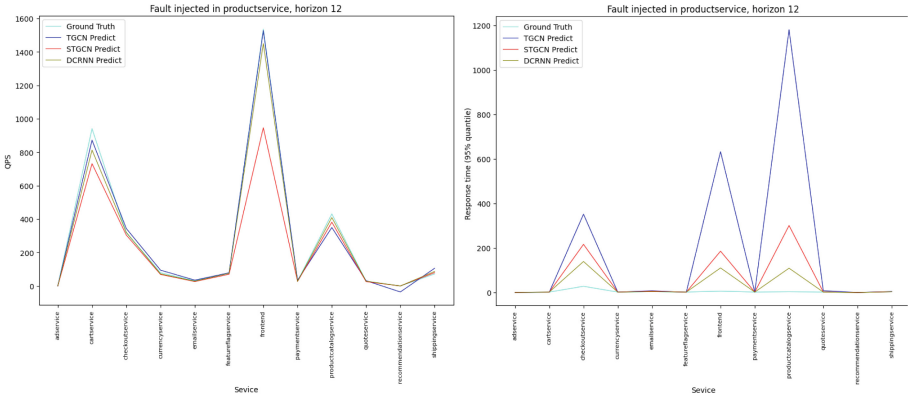

Fig. 7. Prediction for one selected moment of time across all the microservices. QPS (left), time response (right) data with fault injected into productcatalog service. Prediction horizon is 180 s

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A Promising Approach to Detect Early Signs of Disease in Old Age

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Abstract. The article proposes a platform structure that allows correctly, with a sufficient level of statistical significance, to separate a group of patients with the early stages of Alzheimer's disease from healthy controls, patients with late-life depression and people with cognitive impairment of vascular etiology. At the same time, three serious technical problems have been solved: the possibility of secure storage, transmission and provision of data in a form suitable for intellectual processing without disclosing personal information about patients has been implemented; filling in missing data to avoid distortion of survey results statistics; perform joint processing of data obtained at each of the diagnostic installations.

Keywords: Alzheimer's disease · protection of personal information · depersonalization · synthetic data sets

1 Introduction

Neurodegenerative diseases of the brain, accompanied by the development of dementia, represent a wide range of disorders, the common clinical sign of which can be considered a gradual decline in cognitive functions. Around the world, a diagnosis of Alzheimer's disease (AD) appears every 33 s and almost a million newly diagnosed cases are registered every year [1].

Despite the fact that the histopathological picture of AD is relatively well studied, for a long time intravital assessment of specific changes in brain tissue remained extremely difficult due to the lack of technical capabilities for their study and verification. That is why the first clinical criteria for diagnosing asthma were based on an analysis of the clinical picture and the nature of the disease. This has led to a wide range of conditions with different clinical manifestations being classified as Alzheimer's disease. Despite the possibility of a three-level assessment of the degree of probability of the presence of AD within the framework of this approach, however, to make a final diagnosis, a post-mortem histopathological examination of brain tissue was required. Thus, the diagnosis of "Alzheimer's disease" could only be established in the presence of dementia syndrome - a severe, irreversible, progressive and disabling condition, the treatment of which can pursue only very modest goals.

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The accumulation of information about the failure of attempts to restore the cognitive functioning of individuals whose cognitive decline has reached the level of dementia, as well as the emergence of technical capabilities for intravital study of functional and structural changes in brain tissue have become the basis for the development of new diagnostic [2].

At the same time, more than 100 years of experience in evidence-based research has demonstrated the futility of attempts to establish one single cause of the development of asthma, and, consequently, the identification of any one parameter as an indicator of the disease. Not a single sign detected by the above research methods is strictly specific for AD.

The typical onset of AD is a decrease in cognitive functions, primarily impairment of short-term memory, but atypical development of AD is possible. The early signs of Alzheimer's disease are similar to those of other age-related neurodegenerative diseases and early dementia, making early diagnosis of Alzheimer's disease extremely difficult [3].

Due to the extreme complexity of the development of the disease, a number of studies are performed to make a diagnosis, resulting in the formation of several groups of data, including clinical observation, anamnesis, results of experimental psychological tests, as well as data from various measuring instruments (for example, EEG, MRI and others), which have different formats and are processed by different programs and may be characterized by potential incompleteness, inconsistency, and noise. Such data is incompatible with each other without a comprehensive content analysis and non-trivial transformations to forms for which integral analysis is available.

At the same time, doctors can prescribe a different list of studies for each patient, and quite often the doctor's conclusion based on his experience may contradict the results of instrumental diagnostics.

Thus, we have the results of six (and often fewer) types of indirect diagnostics of patients, which are in no way related to each other, but their joint processing would make it possible to determine biomarkers that are associated with AD, which represents a classic problem of "Big Data" processing.

To store and analyze the results of medical examinations of patients at the Research Institute named after V. M. Bekhterev we are developing an information system that should ensure the protection of personal data, and in the future this system should be integrated with other brain research systems within the framework of international collaborations. All this leads to the need to solve three serious technical problems:

1. Possibility of secure storage, transmission and provision of data in a form suitable for intellectual processing without disclosing personal information about patients.
2. Filling in missing data to avoid distortion of statistics
3. Joint processing of data obtained on each of the diagnostic installations and correlation analysis, which allows you to calculate significant features.

2 Safe Handling of Data

The present time can most accurately be described by the word “digitalization.” Access to healthcare results in an ever-increasing amount of data, increasing the likelihood of data loss, corruption, and theft. Therefore, the importance of ensuring data security increases.

Data security has two aspects: the first is the personal data of patients, to which a limited circle of people should have access, and there is data that can be used to solve scientific problems and this is a matter of anonymization. The second is the data transmission medium. Using the Internet provides great opportunities, but does not provide data security, but using an intranet, where everything is protected, does not provide scientists with access to data sets.

A platform that can largely solve the above problems has been proposed by DGT Network (https://dgt.world/) and is called DGT [4]. DGT has a hierarchical topology in which each cluster of decentralized nodes - medical institutions - adapts to a specific business environment, while remaining part of the overall platform. DGT is a hybrid network, meaning that these clusters can have either public or consortium-based provisions to bring everyone together under one platform. DGT can process any digital value: IOT data, identifiers, digital twins, smart contracts, etc.

The complex structure of information exchange in this system is aimed at providing a single information space for different nodes, forming a single reliable copy of data, free from random and intentional errors. Such problems often arise when the system operates without a single center. The logic of checking each transaction and its distribution throughout the entire system (synchronization of registers) is described by a system of rules called consensus.

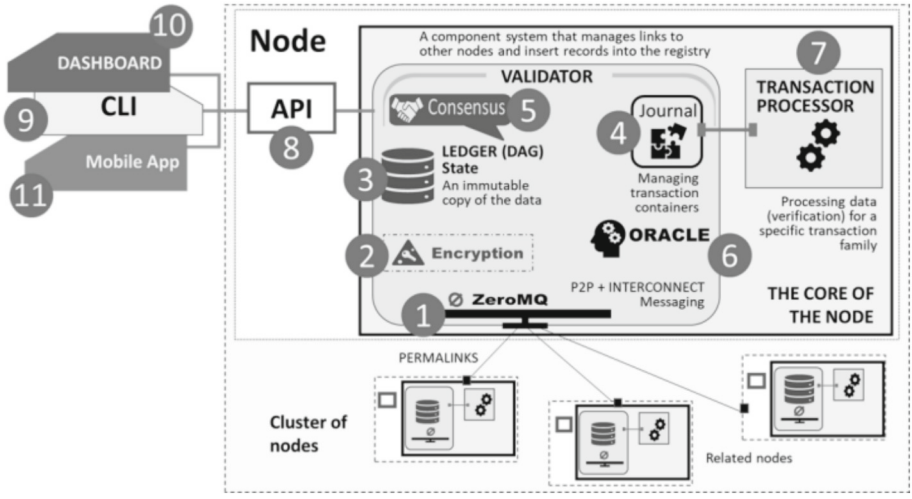

Fig. 1. Conceptual architecture of the DGT-based CFI platform.

The complex structure of information exchange in the described system is aimed at providing a single information space for different nodes, forming a single reliable copy of data, free from random and intentional errors. Such problems often arise when the system operates without a single center. The logic of checking each transaction and its distribution throughout the entire system (synchronization of registers) is described by a system of rules called consensus (see Fig. 1).

3 New Approach to Data Transfer

Recently, one of the most effective approaches is data protection in depth, that is, the use of several sequential measures to prevent access to information by third parties. This approach uses several levels of data protection, which increases system security and reduces the risks of unauthorized access to information. For secure data transfer, an algorithm has been developed for embedding encrypted personal information (full name, year and place of birth, profession, etc.), biometric information (weight, height, etc.), examination results, established diagnoses, etc.) in the form of a QR code into a color image, consisting of the following steps (see Fig. 1) [5]:

1. Preparing messages for QR codes with documentary information.
2. Message encryption for QR codes with documentary information
3. Highlighting the content of the barcode image
4. Dividing the selected content part of the barcode image into several parts
5. Application of geometric transformations of image matrices of barcode parts (rotation by an angle multiple of 90 degrees, matrix transposition, rotation around an axis that coincides with one of the rows or columns, etc.)
6. Write the converted parts of the barcode into different areas of the container image.
7. Accordingly, information extraction is carried out in reverse order.

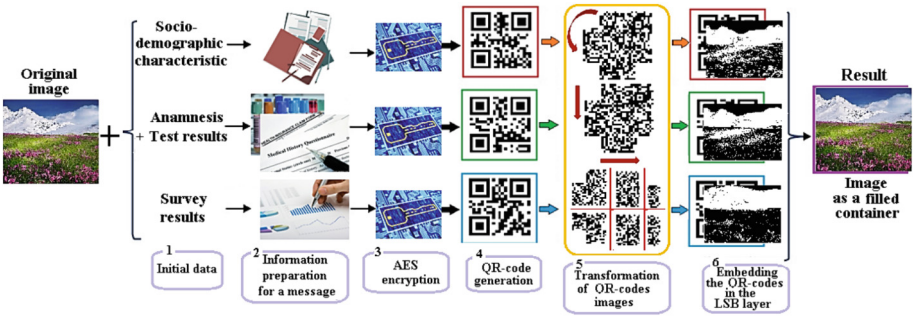

Fig. 2. New approach to data transfer and storing.

It should be noted that container images obtained in this way do not allow us to detect the existence of documentary information in them. The use of color images with embedded QR codes containing encrypted information as a storage and carrier of personal data will ensure the protection of this information, as well as limit public access to it, since

the embedded information can only be read and decrypted if there is an encryption key and knowledge of the structure of recording information.

This technology will make it possible to apply a universal standard when transferring personal data over the network, exchanging information, including through international channels, without losing any part of it and/or replacing it, as well as significantly reducing the losses of medical institutions from data leaks and significantly increasing security processing of personal data.

To effectively solve the problem of making a diagnosis, it is necessary to use all available patient examination data, while ensuring the protection of their personal data. This problem can be solved by anonymizing data.

4 Methods of Depersonalization

Depersonalization methods (classical depersonalization or k-Anonymity model) are aimed at eliminating the connection of individual attributes with identifiers [6]. The main idea for this class of methods is to identify groups of similar records (equivalence classes) that can be attributed to more than one individual. In this case, the main property of the definition of personal data is violated - the correlation of information with a directly or indirectly identified or identifiable individual. The size of this equivalence class (the size of similar records) allows us to calculate the probability of re-identification:

$$P_{datarisk} = \frac{k(D)}{\left\langle \widetilde{E} \right\rangle}$$

Here $\left\langle \widetilde{E} \right\rangle$ is the minimum size of all equivalence classes within the selected data set. If this size is determined by the number of rows in which all indirect attributes match, then this metric is called k-Anonymity. If additional statistical distributions are required in each equivalence class, more stringent metrics are used - ℓ-Diversity or τ-Closeness.

The advantages of this group of methods include their good determinism, resistance to binding attacks, and the ability to calculate metrics. On the other hand, applying the methods to large data sets requires a fair amount of computational effort.

Mondrian Multivariate Algorithm

The most suitable depersonalization method, in our opinion, is the Mondrian algorithm. This is a greedy multidimensional algorithm that recursively partitions the anonymized set into regions, each of which contains at least k-records. This uses the median split method on the attribute with the widest range of values.

The algorithm is named after the Dutch artist Piet Mondrian, whose abstract compositions inspired the geometric approach to sectioning used by the algorithm. The Mondrian algorithm works by partitioning data into rectangular subsets, or "bins," based on the values of attributes in the data set.

The Mondrian algorithm is an extremely useful anonymization tool and can be used for both batch and streaming data. At the same time, the method has some limitations. For example, the partitions generated by the algorithm may be highly dependent on the order of attributes and privacy settings, which may affect the quality of the anonymized data. Additionally, the algorithm can be computationally complex, especially for large data sets.

5 Synthetic Data

The studies have shown that it is necessary to fill in the missing values in the data, since during processing the computer perceives a zero value in the absence of data as an outlier, which is a gross error. The solution to this problem can be the generation of synthetic data.

Synthetic data are sets generated by the system to replace real values. Such sets represent data that is not correlated with real individuals, but retains the patterns of the original set. There are different ways to generate synthetic data. This study used an algorithmic approach.

Algorithmic synthetic data sets

In this case, artificial (synthetic) data is created in accordance with specified algorithms. The advantage of such sets is the predictable profile of the generated set. The disadvantage is the excessive rigidity of the algorithms, the description of which for each set requires additional research costs.

The algorithmic approach is used in situations where the raw data cannot be disclosed due to privacy issues, such as medical or financial data. There are several algorithmic methods for generating synthetic data, including:

1. *Random sampling:* This method involves random sampling from the original data set to create a synthetic data set with similar statistical properties. However, this method can result in biased or poor-quality data if the sample size is too small or if the original data has complex relationships.
2. *Model-based methods:* These methods use statistical models to create synthetic data that mimic the distribution of the original data. Examples of model-based methods include Gaussian mixture models, Bayesian networks, and decision trees.

Since the data has a huge number of gaps, the first step in solving the problem will be to fill them with synthetic data. First of all, the data were checked for normality distributions using various statistical criteria. Also for each analysis, a comparison was made between the mean values and variances between groups of men and women. For all signs graphs were constructed for visual assessment of the distribution of general totality. From the data obtained, a conclusion was drawn about the features, and each feature that was taken into account when filling in the gaps.

1. Filling with a constant value (mean, median, constant – whichever fits the data best): Missing values in a column were filled with statistical metrics such as mean or median, or constant a value preselected based on the context of the data.
2. Filling according to normal distribution: Missing values were filled with randomly selected values from the normal distribution, the parameters of which were determined either from the sample or taking into account reference tests values, if known. This approach allows for better simulate missing data and does not generate outliers.
3. Filling with a constant value with variation: Missing values are replaced with a constant value, but with adding variation to account for diversity in the data. This approach is an improvement on the first method, but it has not been used.
4. Iterative filling using sklearn.IterativeImputer: Missing values are predicted using the model RandomForestRegressor and this process is repeated several times for

clarification of the results. This method was used for features, for whose distribution or other knowledge about the character is unknown data and passes. One can try other models in the future (the sklearn package offers quite a few, but they all require careful selection of hyperparameters) and find a model that provides the best filling in terms of clustering missing data.

6 Collaborative Data Processing

It was noted above that all survey results obtained must be used in close connection, since the problems under consideration may have multi-criteria dependencies that are indistinguishable when using a single source of information. At the same time, the analysis should be carried out on entire sets of patient examination results using intelligent data processing methods based on deep machine learning and multivariate statistical analysis.

The analysis process should be based on complex techniques, the effective use of which requires easily accessible means of handling clinical and biological data, which, in turn, can be implemented through modern cloud and high-performance technologies.As a starting point in solving the problem, it is proposed to solve two problems that are classic for machine learning and multivariate statistical analysis - the classification problem and the clustering or cluster analysis problem. Both tasks are aimed at combining objects into groups according to characteristic common features and further identifying new objects into formed groups.

To achieve the goal of finding informative biomarkers of Alzheimer's disease, the classification task within the framework of the ongoing study is suitable due to the presence of clinical diagnoses. These physician diagnoses can act as predefined categories—classes—into which the patients in question can be placed. However, when solving this problem, it is worth taking into account the possibility of a mistake made by a specialist in the diagnosis made. Such cases are quite acceptable, taking into account all the previously described difficulties in diagnosing one or another type of neurodegenerative disease. The presence of errors in the diagnoses of specialists may not have the best effect on the final quality of the resulting solution. Therefore, it is critical that the diagnosis be correct, which is a significant limitation in the application of classification models. In this regard, applying classification algorithms in isolation may not be the most optimal solution. To achieve better accuracy in predicting classes, it is proposed to use not only clinical diagnoses established by specialists, but also diagnoses based on diagnostic classes obtained through data analysis using suitable methods. This approach to making diagnoses is called "data-driven". One suitable method for automatically identifying classes is cluster analysis.

To solve this problem, a software solution that implements the process of automatic classification of patients with the subsequent use of the resulting diagnostic labels to solve the classification problem. Solving both the clustering problem and the classification problem is equally important for the results of the study.

Classification methods are useful because in most cases they allow one to derive patterns and connections between data explicitly - in the form of functions or a list of conditional rules by which classification was made. Analysis of the obtained functions or rules will make it possible to clearly establish the patterns of interest or state their

absence, as well as discover new ones, if any. Because classification implies the presence of strictly defined categories of patients, among them there will be Alzheimer's patients. In the case of a high-quality trained classifier that can distinguish target patients from others with a sufficient level of accuracy, it will be possible to identify the rules by which the classifier identifies such patients, which can provide greater understanding of how to diagnose the disease. In addition, many classification models make it possible to evaluate the contribution of one or another object parameter (patient test values, be it EEG, MRI or blood test) on the classification result. This in turn can also give specialists a broader view of the nature of the disease.

Cluster analysis, as has been said many times before, allows you to find hidden patterns and new structures in data that would be impossible to detect by other methods. Cluster analysis is more difficult than classification in terms of extracting meaning from the results obtained, because does not provide an interpretation of why certain groups were formed. Interpretation of the resulting groups is already the task of specialists in the field of research. And this is the value of clustering methods - they give researchers food for thought, offer new hypotheses and new space for studying the topic. As part of the study, ideally, in the process of cluster analysis, a cluster consisting primarily of Alzheimer's patients should be identified. Identification of a separate group of such patients will allow for a more detailed comparison of patients in this category with the rest of the observed patients and, potentially, will bring more clarity to the issue of diagnosing

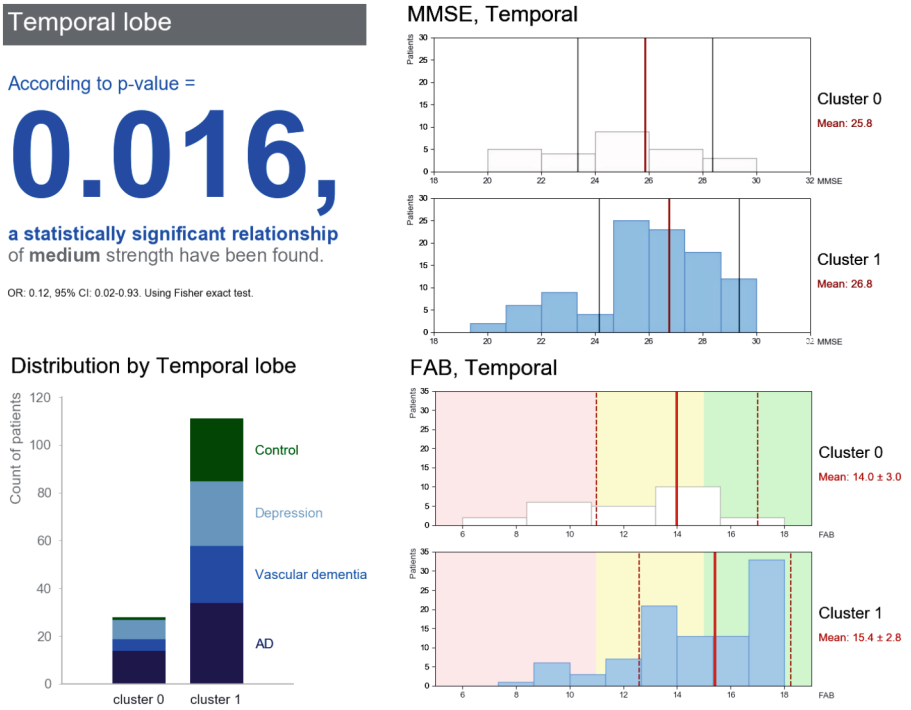

Fig. 3. Research results.

the disease. In addition, as in the case of classification, for clustering algorithms there are also methods that evaluate the contribution of a particular feature (parameter) of an object to the formation of a cluster. Knowing which feature contributed to the formation of the cluster to a greater extent can give specialists a deeper understanding of the nature of each group of patients and additional information for analyzing the formed categories. Together, all of the above should contribute to the discovery of new biomarkers of the disease.

The use of this approach to evaluate data from individuals with complaints of memory loss showed that cluster analysis allows one to correctly, with a sufficient level of statistical significance, separate the group of patients with the early stages of Alzheimer's disease from healthy controls, patients with late-life depression and individuals with cognitive impairment of vascular etiology (Fig. 2). The data we obtained as a result of multidimensional statistical processing allows us to talk about the possibility of correctly separating the indicators of individuals with neurodegenerative changes in the brain from those who are conditionally healthy (Fig. 3).

7 Conclusions

1. It is not enough to carry out measurements using only one, no matter how complex, diagnostic tool to identify illness of the elderly people.
2. To identify correlations, it is necessary to use data from at least three diagnostic installations.
3. To obtain reliable results, it is necessary to fill in all fields to perform statistical analysis in order to avoid distortion of the diagnosis.

The article proposes a platform structure that allows correctly, with a sufficient level of statistical significance, to separate a group of patients with the early stages of Alzheimer's disease from healthy controls, patients with late-life depression and people with cognitive impairment of vascular etiology. At the same time, three serious technical problems have been solved: the possibility of secure storage, transmission and provision of data in a form suitable for intellectual processing without disclosing personal information about patients has been implemented; filling in missing data to avoid distortion of survey results statistics; perform joint processing of data obtained at each of the diagnostic installations.

The data obtained as a result of multidimensional statistical processing allow us to talk about the possibility of correctly separating the indicators of individuals with neurodegenerative changes in the brain from those who are conditionally healthy.

This approach provides ample opportunities for further research in the field of psychiatry and neurology for the diagnosis and treatment of a wide range of mental and neurological disorders, using new categories of data and new highly effective data analysis methods for analysis.

To turn our research into practical medical technology it is necessary to carry out a number of computational experiments, each of which is specified by the following characteristics:

– Name and description of the dataset used for experiment, with details of its preprocessing

- Description of the feature extraction method
- Description of the clustering method
- Description of the resulting clusters
- Graphical presentation of results
- Calculation of quality assessment metrics
- Based on the results obtained, compare different combinations of methods and find the most preferred ones (by time, accuracy or other parameters)

Background Information

Personal data – information relating to a directly or indirectly identified or identifiable individual.

Processing of personal data - collection, recording, systematization, accumulation, storage, clarification (updating, changing), extraction, use, transfer (distribution, provision, access), depersonalization, blocking, deletion, destruction of personal data.

Personal data protection is a set of measures aimed at protecting information relating to a specific individual or determined on the basis of such information.

Violation of the security of personal data is divided into three categories: confidentiality (inaccessibility of information to unauthorized persons), integrity (preservation of completeness and consistency of information), availability (information is available and ready for use by authorized participants in information exchange).

Anonymization - the impossibility of re-identifying data, the irreversibility of depersonalization even when using additional information. Moreover, theoretically, if there are unlimited resources, any anonymous data can be re-identified.

Pseudonymization is the replacement of identifying information with a pseudonym (with the result that personal data can no longer be attributed to a specific data subject without the use of additional information, and such additional information is stored separately and is subject to technical and organizational measures to ensure confidentiality). Currently, the main attention should be paid to data exchange mechanisms (not only storage and reception). It is necessary to move to dynamic security based on changing parameters and scenarios, taking into account the context and characteristics of the data itself.

Depersonalization - actions as a result of which it becomes impossible, without the use of additional information, to determine the ownership of personal data to a specific subject of personal data.

Direct identifier is an attribute of personal data that allows you to identify the subject of personal data without involving additional information or other attributes. Example – passport number or TIN.

Quasi-identifier - an attribute of personal data that allows you to identify the subject of personal data together with other attributes - quasi-identifiers (that is, it is quite well correlated with the subject of personal data). Example – presence of a rare disease + address = unambiguous correspondence with a specific individual – subject of personal data.

An indirect identifier is an attribute of personal data that allows you to identify the subject of personal data only when additional information is involved.

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Analysis of Attacks on Continuous Authentication Methods and Ways of Defending Against Them

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Abstract. User authentication remains one of the most pressing issues in modern cybersecurity, with traditional methods increasingly failing to meet the modern challenges. In particular, there is now a plethora of attacks traditional authentication algorithms are vulnerable to, and a successful attack can be seriously damaging for a system as a whole. For this reason, Continuous Authentication (CA) emerged as a new approach to securely authenticate users in a distributed system, with diverse methods using such technologies as machine learning, neural networks, behavioural biometrics, etc. However, several new attack vectors have been suggested that might compromise even CA-protected systems. In this article, we provide an analysis of possible attacks on various CA algorithms. Furthermore, we discuss the attacks' limitations, various factors that might improve authentication systems' resilience, as well as proposed defense mechanisms that could provide protection against these attacks. We conclude that most common CA methods today, while a step-up compared to traditional authentication methods, are still susceptible to being subverted, and implementing defense mechanisms and adopting security best practices should be an important consideration while designing a user authentication system.

Keywords: Continuous Authentication · Adversarial Attacks · Machine Learning · Cybersecurity

1 Introduction

1.1 User Authentication in Distributed Systems

User authentication, along with user identification and authorization, is one of the main components of the access granting process of any information system. In particular, to authenticate a user means to confirm a user's identity – that is to say, to make sure that the user is really who they claim to be.

There are various ways to confirm a user's identity, and over the decades, a great number of various authentication methods has been developed – from simply relying on a user knowing some secret piece of information (e. g. a password) to basing the authentication mechanism on a distinctive part of human anatomy or physiology (this

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includes diverse biometric methods such as fingerprint scanning, face recognition, gait-based user recognition, and much more). The basic goal, however, remains the same no matter the principle used – to be able to tell, with high levels of accuracy, whether the person seeking to gain access to the system is a legitimate user or an impostor attempting to pass themselves off as a legitimate user.

User authentication is one of the most essential parts of an information system's security architecture. Its importance is obvious – if a system cannot tell a legitimate user apart from an impostor, it means that a malicious actor can compromise the system, causing serious damage. Just as importantly, a legitimate user can be prevented from accessing the information system.

1.2 Common Attacks on Authentication Methods

Just as authentication methods are numerous and diverse, various authentication attacks have also been developed [1].

An authentication attack can be understood as a sequence of actions aimed at subverting an authentication algorithm. Whereas user authentication aims to only allow legitimate users access to the protected system, the goal of an attack is to gain access in spite of not being a legitimate user. This means either obtaining the credentials used to confirm a user's identity or bypassing the credential part altogether and directly gaining access through some other means.

Below, some of the most common authentication attacks are listed, along with a brief description for each.

Brute force attack is the simplest form of attack on a password-based authentication system, being an attempt to simply guess a password via trying different possible symbol combinations. Other similar approaches include dictionary attacks (using a list of common passwords) and password spraying (trying several common passwords across a large number of users, thus bypassing a limit on authentication attempts for a single user).

Phishing refers to use of various social engineering techniques that aim to trick people into compromising their own security systems, whether by revealing authentication information to an attacker or by unknowingly installing malicious software. Various types include broad phishing, where an attacker targets a large group of users to try to gain access to one or a few accounts (similar to password spraying), and spear phishing, where few targets are carefully chosen and analyzed before launching the attack.

Credential stuffing makes use of the fact that a typical user has various accounts on multiple resources – dozens, or even hundreds separate pieces of authentication information – as well as of the fact that many users tend to recycle their passwords or otherwise use the same authentication information on different websites [2]. It means that if an attacker gains access to a certain user's credentials (e. g. from a website breach, which are common [3]), they can try to use the same credentials for the user's other accounts.

Man-in-the-middle attacks (MitM) include an attacker intercepting a network connection between a user and an information system the user is trying to authenticate in, and then getting access to the user's authentication credentials, or obtaining the session token and using it to log in under the user's guise.

Hybrid attacks combine two or more attack approaches. A typical example is a combination of dictionary and brute-force attacks, where the attacker assumes that the user might make their password a little different from a standard one that would appear in a dictionary. So the attacker uses a list of typical password, like one would in a regular dictionary attack, but also applies the brute-force approach to every password in the list, changing them slightly until a match is found [4].

Other attack types also exist, such as smudge attacks, thermal attacks, replay attacks, etc. [5, 6].

In numerous data breaches that occurred over the last several years, insufficiently secure authentication was a serious factor. According to 2023 Data Breach Investigations Report by Verizon [7], 74% of all breaches include such elements as use of stolen credentials and social engineering, and phishing in particular made up 12% of external attacks.

For this reason, traditional authentication schemes are widely considered to be "broken", i. e., not up to the task of protecting an information system against various possible types of attacks [8].

1.3 Continuous Authentication

The deficiencies of traditional user authentication, and the need to better protect the information systems' integrity, led to the development of new approaches to authentication. In particular, continuous authentication – or CA for short – is a new strategy that reimagines one of the most basic parts of securing a system: the notion of a "security perimeter".

Succinctly put, a major weakness of any traditional authentication system is the fact that the authentication process is performed only once – at the beginning of a user's interaction with the system. If the user, whether legitimate or not, "passes" the authentication stage, they get access to the system or a part of the system for the full duration of the system. No further actions to ensure the user's legitimacy are taken, and if an attacker hijacks the session – as it is possible to do via some of the attacks described above – the system is guaranteed to be compromised.

CA algorithms, on the other hand, continue to verify the user's identity throughout the session. This means that instead of relying on a single authentication result, which is unlikely to be perfectly accurate, the security mechanism can use an aggregate of multiple authentication results to determine whether the user is legitimate. Furthermore, even in case of session hijacking, the system remains protected, as the hijacker still has to undergo repeated authentication attempts.

In a previous work [9], we have analyzed the most common CA methods in use today. They are as follows.

Keystroke-based user recognition is based on the principle that each person's way of typing text via a keyboard is distinct and can be used to tell different people apart, in a similar manner to how one might identify a person's handwriting. Multiple factors can be used to establish a user's "signature"; how long it takes to press a key or release it, the length of pauses between key presses, analyzing ways of entering common words and key combinations, etc. Machine learning is a useful tool here, just as it is with other approaches to CA.

Face identification is a common approach in both traditional and continuous authentication, founded on the fact that each person's face has a number of "landmarks" – in other words, distinct characteristics – the combination of which can be used to confirm the person in question's identity, by comparing the digital representation of the features to a database entry corresponding to the relevant user. In CA, this process happens throughout the session, requiring constant or frequent usage of a video camera; on the other hand, each individual recognition does not need to be perfectly accurate – only after some number of attempts ending in mismatch does the authentication mechanism "raise a red flag".

Mouse movement recognition is a more recent approach, based on the unique way each user moves their mouse. Pressing and releasing mouse buttons is also a factor. Because a mouse and a keyboard are often used in tandem, there has also been some research on combining mouse movement-based and keystroke-based user recognition algorithms.

Touch gesture-based recognition is used as a CA method comparable with keystroke- and mouse movement-based recognition for devices that are equipped with a touchscreen. Here, the way a user "swipes" the screen is considered, based on such characteristics as a touch gesture's position, trajectory, finger pressure, etc. With mobile devices being increasingly widespread, this approach is also gaining popularity.

Behaviour-based recognition can be broadly defined as analyzing the actions a user usually performs throughout a session, and using them to build a model of a given user's regular behaviour. The actions considered can vary widely – from physical actions like walking to the patterns of user's interaction with the information system (e. g., sending and receiving data, using certain applications, etc.). If a user's actions during any given session differ from the regular patterns in a major way, the security mechanism will call for additional checks on the user's identity. This means that behaviour-based algorithms are usually employed in tandem with other means of user authentication.

A brief summary of the methods is shown in Table 1 below.

Table 1. Continuous authentication methods.

Method	Based on
Keystroke-based	How the user presses the keys, enters certain combinations, etc
Face recognition	Continuous observation of the user's face via a camera
Mouse movement	How the user moves the mouse, clicks the mouse buttons, etc
Touch gesture	How the user interacts with a touchscreen device, presses, swipes, performs multi-touch gestures, etc
Behaviour-based recognition	Whether the user's actions while interacting with the system resemble that user's regular action patterns

The list above is by no means exclusive, and new CA methods are constantly being developed and refined. For instance, in another article [10] we explore CA algorithms

that can be used in an IoT environment, including methods based on gait analysis, context cues, and other factors.

CA is effective in protecting against most attacks we described earlier [11]. However, some works have emerged recently exploring the possibility of compromising even CA-protected systems. In the remainder of this article, we investigate known adversarial attacks that could conceivably "defeat" CA, their estimated efficiency, as well as possible ways to ensure better protection against such attacks.

1.4 Article Structure

The article is organized as follows.

In Part 1, we briefly introduce the concept of user authentication, list common attacks on authentication systems, and discuss continuous authentication methods in use today.

In Part 2, we review the existing literature on the topic of attacks on continuous authentication.

In Part 3, we explore existing ways to attack various CA methods.

In Part 4, we go over the attacks' limitations, as well as possible ways to defend against the attacks.

In Part 5, we conclude the article, propose features and best practices for prospective CA systems, and outline future research directions.

2 Literature Review

In general, the topic of attacks on CA-protected systems remains little explored in the literature of the field [12]. However, several works have been published that detail possible ways to compromise the security of such systems.

In this section, we give a brief review of the current research on the topic of adversarial attacks on CA.

In **"Adversarial Attacks on Deep Learning Systems for User Identification based on Motion Sensors"** [13], C. Benegui and R. T. Ionescu analyze authentication systems based on motion sensors and deep learning methods. Several methods for generating adversarial examples that can aid the attackers with impersonating a legitimate user are studied. Experiments with various DNN architectures are carried out, and both architecture-specific and universal possible attacks are discovered. The authors show how adversarial input can be effective in subverting DNN-based mechanisms for confirming mobile user identity.

In **"Impact of injection attacks on sensor-based continuous authentication for. smartphones"** [14], L. Gonzalez-Manzano et al. focus on injection attacks that can possibly subvert user authentication based on behavioural biometrics. In particular, the authors explore a possibility of attacking a mobile phone authentication mechanism based on sensor data. Location, gyroscope, and accelerometer data are considered as authentication factors due to their widespread usage. The authors demonstrate how injection attacks can be effective against user behaviour-based CA even with lack of previous knowledge about the user. Estimated threat detection time in various attack

scenarios is also considered. Finally, the authors consider proposals about defending against injection-type attacks on smartphones.

In **"GANTouch: An Attack-Resilient Framework for Touch-based Continuous Authentication System"** [15], M. Agrawal et al. explore the topic of attacks on CA methods based on touch strokes, as well as ways to defend against such attacks. Several possible attack strategies are considered, as well as countermeasures against such attacks. The authors conduct experiments with both existing touch-based algorithms and their own novel CA framework, and demonstrate how to increase the approach's resilience against adversarial attacks. The question of gender fairness of touch-based methods is also touched upon.

In **"Continuous Authentication against Collusion Attacks"** [16], P. Lyu, W. Cai, and Y. Wang introduce a new type of attack model on CA called a collusion attack. The authors analyze the attack's feasibility and experimentally prove that their approach is able to successfully compromise certain gait-based CA methods. Furthermore, a new multi-cycle scheme to defend against collusion attacks is proposed.

In **"Template Inversion Attack against Face Recognition Systems using 3D Face Reconstruction"** [17], H. O. Shahreza and S. Marcel present a new attack that uses a geometry-aware generator network to generate 3D face images that can trick a face recognition-based CA system. They explore various attack scenarios, conduct experiments, and also discuss the limitations of the proposed attack, as well as certain ethical considerations.

In **"Malboard: A novel user keystroke impersonation attack and trusted detection framework based on side-channel analysis"** [18], N. Farhi, N. Nissim, and Y. Elovici develop a sophisticated attack on keystroke-based continuous authentication mechanisms. The authors demonstrate how their attack can evade specialized security tools and successfully attack a protected system in the majority of cases. They also present three detection modules that can detect keystroke injection attacks, including the novel attack they propose.

3 Adversarial Attacks on CA Methods

As we noted in the previous section, although the topic of adversarial attacks on information systems protected with continuous authentication mechanisms has been explored relatively little so far, several possible attack angles have emerged. Given the rising popularity of CA as a more secure alternative to traditional authentication methods, analyzing how CA methods themselves might be compromised, and how enhance their resilience against the suggested attacks, is an increasingly important problem.

In this section, various ways to attack continuous authentication-protected systems are explored and evaluated.

3.1 Injection Attack

One of the most promising directions in continuous authentication development is using CA to protect mobile users. It takes advantage of the fact that smartphones already collect various sensor data – including gyroscope data, accelerometer data, location information

and so on – that can be used to develop patterns that uniquely correspond to a certain user (for instance, one's gait, or a manner of walking) and can therefore be applied to the task of user identity verification.

However, the above assumes that the data provided by the phone's sensors are accurate and have not been changed by an outside actor. In reality, however, there are already several proposed methods to influence the sensors' output, from simply distorting it to establishing control over it. These methods can be both hardware-based (e. g. application of magnetic or acoustic pressure to a mobile device) and software-based (data-altering malware).

Two main attack scenarios have been proposed: one where the attacker has no previous knowledge about the victim – and thus does not know the sensor values typical for the user – and one where the attacker obtains knowledge about the victim beforehand, typically through using malware. In both cases, the attack itself includes the attacker somehow getting physical control of the victim's mobile device, and then influencing the device's sensors to inject falsified sensor values. The attack is considered successful if authentication is completed before the security system detects tampering, or the user realizes the device's disappearance.

Based on the attack scenario, two data injection strategies are available – Blind Rate (BR) injection and "Slogger" attack. Both essentially modify a series of sensor readings (formula) into new readings that should trick the authentication system. In BR, all features of the reading are modified by a fixed ratio, whereas the "Slogger" attack, which is only possible with previous knowledge, takes the user's maximum and minimum readings and injects the data randomly between them.

The authors of the article [14] investigate both attack scenarios in various contexts. They note that in some circumstances, the CA system makes a mistake up to 13.2% of the time.

For mobile device sensor data, the Sherlock dataset is used. This dataset was collected from 47 users for a maximum of 36 months, recording location data every minute and gyroscope and accelerometer data every 15 s. Location records consist of 12 distinct features, whereas gyroscope and accelerometer records consist of 90 features.

Injection attacks against mobile devices remain little explored, despite the very real possibility of such attacks succeeding [19].

3.2 Collusion Attack

Another increasingly common CA method is gait-based user recognition. It is based on the principle that each person walks in a distinct manner, which can be used as a way to confirm a human user's identity. This approach can be considered one of the types of biometric behaviour-based user authentication.

In one article [20], three different methods of gait-based user recognition are described: using machine vision, using floor sensors, and using wearable sensors. In all cases, user gait data are collected, preprocessed to reduce noise levels, and then analyzed via machine learning or other approaches to discover a pattern corresponding to a given user and then use it for authentication.

Gait-based approach is especially convenient due to widespread use of mobile devices, which can collect gait data based on the output of various sensors (see also

the subsection on injection attacks above). That said, it has several vulnerabilities the authors of [16] explore in their article.

One of the vulnerabilities in question is that, as shown in subsection above, sensor data can be manipulated by an outside force; this means that gait-based recognition is also theoretically vulnerable to injection attacks.

The other problem is that gait – unlike certain other biometric traits like fingerprints or eye retina – is relatively easy to observe, making it possible to emulate a target user's manner of walking and thus increase the chances that the authentication system mistakes an attacker for a legitimate user. Lyu, Cai, and Wang explore this type of attack.

The basis of their attack is essentially mimicry. By observing the target user's gait, either through video surveillance or in person, and then imitating the gait's distinctive characteristics, such as walking speed and rhythm, the height of the foot from the ground, elbow movement, etc., a sufficiently well-trained attacker has been shown to successfully "fool" a gait-based system.

In general, attacks on gait-based authentication can be classified as zero-effort or passive (the attacker having similar biometric characteristics to the victim) and adversary or active (the attacker actively trying to mimic the victim's biometrics). Here, "collusion attack" refers to the combination of the two.

The authors have gathered gait data from 20 members of an honour guard unit over the course of three months. The subjects are physically similar to one another in terms of age, height, weight, and gender; they were also trained to walk in a specified manner as a part of their duties.

According to the authors, their attack reached the success rate of 39%.

3.3 Template Inversion Attack

Face recognition (or face identification, as described in Part 1) is also a popular method to use in CA systems, and one of the most common biometric authentication mechanisms in general.

Face recognition algorithms use either 2D face images or 3D face models; in general, 3D face recognition is more complicated and computationally demanding, but also offers a higher level of accuracy.

Several attacks against face recognition have been developed. These include print attacks (using static face images), replay attacks (using prerecorded face videos), 3D mask attacks (physical masks of the target's face) [21].

Recently, a novel method of subverting face recognition-based CA has been developed, referred to as template inversion attack. Briefly, this attack, also called GaFaR (Geometry-aware Face Reconstruction), uses GANs (Generative Adversarial Networks) to reconstruct a 3D face model from facial features extracted from 2D face templates [16].

The attack uses a generative neural radiance field (GNeRF) method: a GAN is used to embed the appearance of an object's (a target user's face) in a latent space, and then the GAN's latent code along with camera parameters are fed to a neural radiance field (NeRF) for the rendering process. To train the network, a semi-supervised learning approach is used, based on both real and synthesized images.

There are two main attack scenarios. In the "white-box" scenario, the attacker knows the face recognition model's internal functioning and parameters. On the other hand, in the "black-box" scenario, this information is unknown to the adversary.

During the attack, a generator network learns the mapping from facial templates, and a GAN-based mapping network reconstructs 3D faces. An attacker can inject the generated 3D face model in the authentication process and use it to try to gain access by impersonating a legitimate user.

The authors use several datasets during the experimental stage of their research: the FFHQ dataset (70,000 high quality face images), the LFW dataset (12,233 images of 5,749 people), and the MOBIO dataset (150 people, 12 sessions per person).

The article claims a success rate of up to 17.14%.

3.4 Keystroke Impersonation Attack

Keystroke recognition is one of the oldest CA methods. It can be compromised, but CA tools can generally identify machine generated keystrokes if they are not similar to a human user's input – for instance, many existing keystroke injection attacks are characterized by typing speed not characteristic of a human user.

A new attack called Malboard was proposed that injects malicious commands via keystrokes that imitate a human user's biometric characteristics. It is conducted via a USB device masquerading as a regular keyboard [18].

The USB protocol has certain vulnerabilities that make it easier for an outside adversary to launch attacks. In particular, these are the fact that the host typically allows the USB device to send data that bypass any security mechanisms (e. g. malicious human interaction device (HID) codes can be sent straight to the operating system without any inspection by anti-virus software), as well as the fact that a USB device declares its own identity and characteristics, allowing a malicious USB device to impersonate other similar devices by sending the host false information. These facts make using malware-infected or even specifically built USB an extremely viable attack vector.

In the Malboard attack, a keyboard is physically modified to include a Teensy microcontroller, a USB Host Mini, and ESP8266 Wi-Fi component. Teensy is capable of modifying its own VID (vendor ID) and PID (product ID), making it possible to impersonate a regular keyboard and bypass most anti-keylogger protections (which largely rely on VIDs and PIDs). USB Host Mini makes it possible for Teensy to communicate with a keyboard as a host. Finally, ESP8266 allows Malboard to communicate with a distant attacker and to send the legitimate user's keystroke pattern data.

Once the user connect the keyboard to the computer, Teensy intercepts the user's keystrokes in the manner of a man-in-the-middle attack and uses them to build the user's profile. Once the user has not been active in a while, Malboard can start injecting malicious commands using the profile built. It can also communicate with the remote attacker to request instructions and commands.

The attack types include RSI (remote server injection) and PAI (physical access injection); in the former case, Malboard injects commands by itself as described above, although it can send requests to an outside server, whereas in the latter case, the attacker connects to Malboard and manually types commands, while Malboard modifies the attacker's typing pattern to resemble that of the user.

The typing data were gathered by the authors from 30 human subjects aged 20–38, all used to working with computers (students and university graduates). Each subject performed three distinct tasks, namely username and password input, credit card number input, and free-text input.

According to the authors, depending on the attack type and the detection mechanism employed by the user, Malboard evades notice in 83.3–100% of cases.

3.5 Attacks on Touch-Based CA

There are multiple types of attacks on touch-based CA systems (TCAS). Some of the most common ones – and easiest to implement – include zero-effort, population, and random-vector attacks. All of these attacks include creating adversarial examples in the form of vectors – sets of characteristics that are used by the CA system. The intent is to make the authentication mechanism mistake the generated vector for one related to the actual human user.

In a zero-effort attack, the attack vectors are chosen randomly among those generated by each and every impostor (a user other than the genuine user). This attack is the easiest one to replicate, though obviously the least efficient, since it makes no effort to make the attack vectors resemble the real ones. It is therefore often used to evaluate a TCAS's effectiveness as a baseline of sorts.

In a population-based attack, the attack vectors are generated by taking multiple users' vectors into account, e. g. by using the means of each characteristic. The result is referred to as a "master key" (cf. Creating an "average" male and female face based on a large dataset). A more sophisticated version creates multiple "master keys" by using clustering. In either case, access to a large number of samples is required.

In a random-vector attack, the attack vectors are generated randomly by utilizing prior knowledge, e. g. vector length and minimum/maximum values of the user's vector's characteristics. This method was found to be effective against behaviour-based biometric authentication methods [22].

The authors of [15] have carried out all three types of attacks against TCAS. Four datasets were used: BBMAS-Touch (117 users, 173 swipes per user), Serwadda (190 users, 273 swipes per user), HMOG (100 users, 2275 swipes per user), and UMDAA-02Touch (48 users, 4063 swipes per user).

The article finds that the results vary based on both attack type and authentication system type. The overall results are 7–12% for the zero-effort attack, 14–27.5% for the population attack, and 12.5–21.5% for the random-vector attack.

4 Ways of Defending Against the Possible Attacks

4.1 Defense Against Injection Attacks

The authors of the article [14] stress that mobile device sensors should not be thought of as trusted sources by default, since it is possible for an outside attacker to influence them both by using malware and by applying certain types of pressure on the device itself. The possibility of such an attack, according to the authors, should be considered by the design of the system from the beginning.

In their work, the authors introduce a threshold that determines how many failed authentication attempts – caused by sensor data differing from the original – it takes to classify the source as an attacker and to block the mobile device. The goal is that the authentication mechanism should detect an intruder both accurately (few false positives) and swiftly (so as not to give the attacker sufficient time to cause damage to the system).

According to the article's findings, how well a mobile device can defend against injection attacks largely depends on which sensors are used for user authentication, as well as which methods are employed to differentiate between "right" and "wrong" input values (that is to say, the correct choice of a classification mechanism, such as DSM, KNN, HAT, etc.).

In terms of sensor usage, whereas accelerometer and gyroscope injection results do not differ considerably depending on whether the attacker has prior knowledge about the target – and, therefore, whether the "Slogger" attack can be used – location data injection is harder to be detected if the attacker has information about the target. Thus, location-based CA could be more vulnerable in this case.

Often, the KNN (K-Nearest Neighbour) algorithm is used for the purposes of continuous authentication. In KNN, an instance is classified according to k of its closest members (by distance), where k is a changeable parameter. The authors find that in all cases, the smaller the k parameter used, the better the system is at detecting an intruder. Furthermore, they demonstrate that KNN shows better results in general compared to other algorithms, whether using accelerometer data, gyroscope data, or location data.

4.2 Defense Against Collusion Attacks

The authors of the article [16] propose a defense model that is aimed at resisting collusion attacks, as well as using fewer resources by not introducing additional sensors for CA purposes. It is based on a standard model of gait authentication.

The defense model consists of several steps.

The first step is data collection. A mobile device carried by a user records their motion data while the user is walking. Only accelerometer data are used.

The next step is data preprocessing. First, the motion data are extracted from the raw data using the sliding window; then, noise is removed from the data using a filter; finally, the motion data are converted into a sequence of cycles of a certain length. Abnormal cycles (such as atypical motion caused by the user stumbling) are removed.

The third step is to transform the data from the device's coordinate system by using the device's body inclination angles.

The final step is to compare the resulting cycles in order to measure their similarity to those of a genuine user. KNN classification algorithm is used for this purpose, and five cycles closest to the "center" (the cycle with the smallest sum of distances from other cycles) are submitted for comparison.

The proposed defense system uses confidence scores to determine if the user should be authenticated. A threshold is set, and the confidence score is calculated based on whether the resulting distance (similarity between the submitted cycles and the genuine user's template) is above the threshold. In order for the authentication to be successful, the confidence score must exceed 50%.

4.3 Defense Against Template Inversion Attacks

The authors of the article [17] introducing a new template inversion attack note that several factors can limit their attack's success.

One of these factors is bias in the generated faces concerning such characteristics as race and age. In particular, the authors note that their adversarial examples generated during a white-box attack showed bias for dark skin and old age. One possible reason for the bias's existence is the datasets used for training the models being themselves inherently biased.

Another factor is that, surprisingly, face recognition models with higher accuracy are more vulnerable to the proposed attack. On the contrary, models with worse recognition performance are associated with more failed attack attempts.

Although defense strategies are not discussed in detail, the article encourages the development of more secure face recognition systems, as well as using biometric template protection schemes proposed in the literature.

4.4 Defense Against Keystroke Impersonation Attacks

As the authors of the Malboard attack [18] noted, most keystroke impersonation attacks can be detected by existing security systems that analyze keystroke characteristics and dynamics and detect non-human patterns. However, more sophisticated attacks such as Malboard are capable of imitating all of a regular keyboard's features, so additional defense strategies are required.

Three main strategies include manual inspection (checking once before connecting a device), continuous inspection (regular inspections throughout the device's use), and combined inspection (combining both previous strategies). Since Malboard relies on hardware installed in a keyboard, detecting the malicious device with the naked eye is possible.

In order to detect the Malboard attack, a detection framework can make use of the following factors: power consumption, vocal keystroke sound delay, and typo deletion. Power consumption refers to the fact that additional hardware requires additional power to function, vocal keystroke sound delay is the result of Teensy acting as the middleman inside the keyboard, and typo deletion makes use of the fact that Malboard is not capable of handling keyboard corrections like a human user would.

There are limitations both to the Malboard attack (multiple person using the keyboard, multi-factor authentication) and to some detection methods (noise preventing keyboard sound analysis, typo deletion detection decreasing usability, etc.).

4.5 Defense Against Touch-Based Attacks

While studies such as [23] have suggested that raw data level distance-based biometric authentication methods are more attack resilient, they also have higher error rates compared to machine learning-based ones. Thus, the authors of [15] chose a machine learning-based method for their authentication mechanism.

The article introduces a Generative Adversarial Networks assisted TCAS framework (G-TCAS) and compares it against traditional, or "vanilla", TCAS methods (referred to as V-TCAS).

Compared to V-TCAS, which work by extracting features from a genuine user's touch gestures and then train the authentication models based on these features, G-TCAS adds a pair of GANs into the process. The first, Genuine-GAN, generates swipes similar to those of a genuine user. The second, Impostor-GAN, generates swipes similar to impostor swipes (real swipes belonging to the impostors). Both GANs consist of a discriminator and a generator, trained simultaneously. The goal of including an Impostor-GAN is to help the authentication framework separate the genuine data from the injected one more effectively.

According to the authors, GAN-assisted touch-based continuous authentication mechanisms are more resilient to all three types of attacks discussed in the previous part (zero-effort, population, and random-vector attacks).

The authors also note that a population-based attack is the most damaging type of the three, and encourage future researchers to test their systems under all three attack types so as to avoid misleading performance results (e. g. an authentication mechanism might be highly resilient to a zero-effort attack, but less so to a population-based or a random-vector attack).

4.6 Attack and Defense Summary

A short summary of proposed attacks on various continuous authentication-protected systems and possible ways to defend against them is presented in Table 2.

Table 2. Attacks on CA-protected systems.

Attack	Description	Experimental dataset(s)	Success rate, %	Defense strategies
Injection attack	Capturing a mobile device and injecting sensor data via malware or magnetic/acoustic pressure, either at random or based on previous knowledge of the user	Sherlock dataset (47 users, 36 months)	13.2	Choosing hard-to-spoof sensor types and ML techniques, not treating sensors as trusted sources
Collusion attack	Mimicking the user's gait based on observing their gait and obtaining various details of the gait	Original dataset (20 subjects, 3 months)	39	A multi-step defense mechanism analyzing and transforming gait data, using confidence scores to determine the user's authenticity

(*continued*)

Table 2. (*continued*)

Attack	Description	Experimental dataset(s)	Success rate, %	Defense strategies
Template inversion attack	Generating a 3D reconstruction of the user's face from 2D face images	FFHQ (70,000 images) LFW (12,233 images of 5,749 people) MOBIO (150 people, 12 sessions per person)	< 17.14	Exploiting bias in adversarial examples, employing biometric template protection schemes
Keystroke impersonation attack	Keystroke injection via a keyboard-impersonating USB device, which intercepts keystroke data and builds the victim's profile	Original dataset (30 subjects, 3 tasks per subject)	83.3–100	Detection based on power consumption, keystroke sound, and typo deletion
Attacks on touch-based CA	Zero-effort attack (use random existing vectors) Population attack (generate average vectors based on large datasets) Random-vector attack (generate random vectors based on previous knowledge)	BBMAS-Touch (117 users, 173 swipes per user) Serwadda (190 users, 273 swipes per user) HMOG (100 users, 2275 swipes per user) UMDAA-02Touch (48 users, 4063 swipes per user)	7–12 (Zero-effort) 14–27.5 (Population) 12.5–21.5 (Random-vector)	Using GAN-assisted touch-based authentication, testing authentication methods against various attack types

5 Conclusions and Future Work

5.1 Overall Conclusions

Continuous authentication is a novel approach to user authentication in information systems. Its main principle is to confirm the user's identity throughout the session, as opposed to just once at the beginning of the user's interaction with the system. Various CA algorithms have been developed, based on factors ranging from keystroke dynamics to user gait.

CA is, as a rule, significantly more secure compared to traditional authentication, and can protect a system against multiple common attack types. However, as we have seen, CA methods are far from being invulnerable from outside influence, and it is possible for attackers to subvert them and gain illegitimate access to a system.

In particular, we have explored injection attacks, collusion attacks, template inversion attacks, keystroke impersonation attacks, as well as attacks on touch-based CA including zero-effort, population, and random-vector attacks. All those attacks are aimed at different types of CA and have demonstrated varying levels of effectiveness, but it can be stated with confidence that the most common CA methods as of today are all potentially vulnerable to certain types of attacks.

Ways to protect against the aforementioned attacks have also been suggested, as well as the attacks' limitations. In many cases, choosing the best available algorithms and optimal input data drastically improves the CA methods' resilience, whereas in other cases, developing new and improved defensive schemes is key.

Machine learning is an essential tool for implementing efficient continuous authentication schemes. ML-based methods were used as a part of defense mechanisms against various types of attacks investigated in this article. Investigating the best ML algorithms for application in a user authentication context, as well the optimal ways to choose their parameters, is therefore an important research direction in the field of cybersecurity.

5.2 Proposals for Resilient CA Methods

Based on the research carried out in this article, we can propose several features and best practices that could potentially make future continuous authentication methods more secure in the face of the novel attacks.

Firstly, a continuous authentication system should use confidence scores and set thresholds for recognizing a given user as a possible threat. CA, like any other security system, always involves a trade-off between security and user convenience; modifiable thresholds allow the authentication mechanism to be more flexible, allowing a certain amount of non-standard responses from a legitimate user while also quickly and precisely identifying potential threats based on repeated authentication failures.

Secondly, several different data sources can be used for authentication. We have seen that some types of data are more vulnerable to certain attack compared to others (e. g., location data compared to accelerometer and gyroscope data). If possible and practical, a hybrid authentication system should be developed.

Thirdly, the authentication mechanism should be tested against various possible attacks, instead of using only the simplest ones to simulate. Furthermore, periodical checks are also essential, as seen with the keystroke impersonation attack. Various hard-to-fake characteristics can be used to make sure a CA system was not compomised.

Fourthly, the number of data sources treated as automatically trustworthy should be limited as much as possible. As shown above, information such as mobile device sensor data can be tampered with by outside forces, leading to a possible vulnerability in an authentication mechanism based on this information. Similarly, USB devices that can bypass security software and send false information to the system are also a potential source of danger. CA methods should follow the Zero-Trust paradigm – "never trust, always verify".

Finally, the novel attacks such as ones analyzed above should be kept in mind while designing an authentication system. CA is effective against "traditional" attack types, both simple and hybrid, but the methods and algorithms used to achieve continuous authentication can also have inherent weak points. As an example, gait-based authentication means that a user's gait can potentially be observed and copied, and an attack has already been developed that takes advantage of this fact.

5.3 Future Work Directions

Future work directions include further research on the topic of attacks on continuous authentication methods and the defense mechanisms capable of increasing the methods' resilience. In addition, we plan to develop a novel CA framework and test it against the new attacks discussed herein.

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Analysis of Privacy Leakage Risks in the Context of Security Threats Associated with Digital Device Fingerprinting

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Abstract. In the modern field of data processing, operations are often conducted within distributed systems, where information of individual users is shared across multiple servers. In such a context, users aim to protect their privacy despite the inevitability of transmitting their device parameters to servers, which occurs almost automatically. One of the main risks is the transmission of device hash identifiers (so-called "digital fingerprints") along with private statistical information, which can lead to the near-complete de-identification of users by external organisations. This risk is exacerbated by the potential use of additional statistical data that can be associated with a user.

This study proposes an analysis of existing methods for assessing the level of privacy and the effectiveness of various algorithms in maintaining differential privacy. The paper explores approaches to assessing the leakage of private data in scenarios where the security threat is associated with the computation and transmission of digital fingerprints of devices, representing a significant interest in developing more reliable data protection methods in distributed processing systems.

Keywords: Differential privacy · Security · Privacy leak · Statistics · Fingerprint

1 Introduction

In the big data era, advancements in information technology have significantly improved the quality of services and living standards, thanks to the growth in available information volume and its processing. However, with the increased accessibility of data, there arises a heightened necessity for the protection of personal information privacy. This challenge compels governments and organizations worldwide to develop and implement effective data protection mechanisms, underscoring the crucial significance of privacy in today's information society.

Many intergovernmental organizations are actively working on preserving personal privacy and have established operational regulatory and legislative acts.

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The European Union is a pioneer in the realm of individual data privacy, having adopted the General Data Protection Regulation (GDPR) in 2016 [1]. Following this, several countries outside of Europe have progressively introduced and enforced privacy laws or regulations, such as Brazil's General Data Protection Law (LGPD) [2], India's Personal Data Protection Bill (PDPB) [3], and Russia's "Personal Data Protection Law".

Despite these efforts, administrative methods of protection sometimes fail to produce the desired outcome. For example, in 2018, the British analytics company Cambridge Analytica accessed Facebook (Meta) user data, resulting in the leakage of at least 80 million units of user information [8]. The data of approximately 500 million customers of the world's largest hotel chain, Marriott, were stolen from its reservation database [9]. Security Magazine published a list of the "best" Top-12 data breaches in 2019 [10], which included the largest American real estate title insurance company, First American Financial Corp, that exposed transaction data of about 885 million individuals, and job seekers in China.

A data breach by the developer and manufacturer MongoDB led to the disclosure of more than 200 million job candidate records. Such information leakage incidents have been occurring one after another in recent years, causing people to grow increasingly concerned about the security of their personal information. These data losses are related to human factors; however, these leaks become a rich source of auxiliary information.

It is evident that relying solely on laws and regulatory acts is insufficient for maintaining confidentiality; hardware and software support for privacy protection methods is required. Countless methods for assessing privacy preservation have been developed, based on maintaining anonymity (for example, k-anonymity [5], l-diversity [6], and t-closeness [7]), which require initial assumptions about specific attacks and knowledge of the volumes of protected data. The research covers ever-new aspects of privacy preservation, considering various combinations of threats.

Academic research in the field of personal data privacy preservation continues unabated as new threats to confidentiality and issues in data science applications emerge. It can be asserted that one of the most successful concepts for assessing confidentiality is the concept of differential privacy [11,15,16]. Introduced by Cynthia Dwork, Frank McSherry, and others [15], this concept ensures that an individual participating in a process that involves further data processing will not face significantly increased risks due to their participation. This guarantee is achieved by declaring that the result of data processing does not substantially (in a controlled manner) depend on whether each individual participates or not.

Thus, differential privacy is a mathematically rigorous definition of privacy compliance conditions, suitable for analyzing large data sets and equipped with a formal measure of privacy loss [11,15]. Differential privacy algorithms strictly take an ϵ parameter as input, which limits the permissible loss of confidentiality for any algorithm execution and offers a specific trade-off between privacy and utility. The concept of cumulative privacy loss has been proven correct, as well

as the possibility of post-processing under the same conditions. Previously, we discussed the theoretical basis for spending the differential privacy budget and proposed an architectural solution [37]. Currently, an extensive theoretical basis has been developed for a large number of relaxed requirement protocols, the so-called (ϵ, δ) - differentially private protocols, guaranteeing a privacy loss of no more than ϵ, with a probability not exceeding $1 - \delta$. Typically, δ is considered "cryptographically" small, this relaxation often provides asymptotically better accuracy than pure differential privacy at the same ϵ value, even when δ is very small.

On the other hand, differential privacy, as originally conceived, does not preclude the possibility of privacy breaches given associative data. In other words, an adversary could exploit correlations between data fragments to compute confidential information about an individual using special mechanisms, as justified in the work "On the Free Lunch" [23] and well demonstrated in "Dependence Makes You Vulnerable: Differential Privacy Under Dependent Tuples" [24]. This work describes how a curious person, by gaining access to a record containing a list of social network friends, virtually obtains a complete probabilistic assessment of user connections.

In their paper [26], Cynthia Dwork and co-authors proved that under certain conditions, no DP mechanism that offers some non-zero utility can prevent the disclosure of information if adversaries possess auxiliary information about the secret data of the storage. This is because an adversary can use auxiliary information to disclose more information than the privacy mechanism assumes. An illustrative example is given in [26]: suppose the exact height of every individual is a secret, and consider a database containing measurements of people's heights across different nationalities. Suppose differentially private statistics are provided - average heights of women of various nationalities. If an adversary has auxiliary information that a certain individual is two inches shorter than the average Lithuanian woman, they can determine that person's exact height by simply subtracting two numbers. This relatively simple example turns into a significant problem under certain conditions.

One such significant condition is the prevalence of various digital devices that can be confidently identified. Fingerprinting or digital fingerprint is a device identification method that uses unique characteristics and parameters of the device, such as configuration, browser data, or hardware features, to determine and track the device. This method can be used for various purposes, including analytics, security, and advertising, but it can also raise questions about user privacy and confidentiality, as it may allow identifying them without their explicit consent.

Moreover, obtaining a digital fingerprint from a device can be accomplished by various methods and in several forms. Here are a few common ways: browser fingerprinting, device fingerprint, IP address and network characteristics, cookies, mobile device fingerprint, and app fingerprint. This topic is well-explored in many works, for instance, in [27,28], and is vigorously used for different purposes.

2 Problem Statement

The study begins with an analysis of the contemporary digital environment characterized by the widespread presence of devices and software capable of tracking users' actions (e.g., sensors in smartphones and trackers in browsers). These tools enable constant monitoring of users even without the transfer of their data. Such observation is stochastic, allowing it to be assessed and analyzed from a scientific standpoint.

This research aims to systematize and study methods for evaluating necessary data perturbations before their transmission to ensure confidentiality within the Local Differential Privacy (LDP) framework. Special attention is given to analyzing entropy, mutual information, and the data transmission channel capacity in scenarios where interaction between the client and server occurs under uncertainty and the potential presence of additional information from potential adversaries.

The main research directions include:

1. Investigating entropy assessment algorithms in various notations, considering privacy and data confidentiality requirements not only in untrusted dialogues but also in scenarios with a known scale of privacy leakage;
2. Examining existing assessments of potential privacy loss for aggregated representations of digital fingerprints of devices or browsers in both one-try processes and interactive dialogues;
3. Exploring various methods of applying LDP to assess privacy loss and determine their effectiveness in the context of this problem;
4. Studying the impact of noise addition algorithm parameters, and consequently, changes in privacy levels on the accuracy of privacy loss estimation;
5. Identifying metrics and methods for evaluating the quality of privacy level assessments in untrusted dialogues.

The central goal of this work is to research and test reliable methodologies for assessing the risks of private information leakage. These methodologies aim to ensure a high level of data protection. Special focus is placed on conditions of untrusted data exchange between the client and server and the use of digital fingerprints of various origins.

3 Problem Relevance

The issue addressed in this research is highly relevant in the contemporary data processing and privacy sphere. Here are several key aspects that underscore the relevance of this problem:

– **Data Privacy Protection**. In the context of collecting anonymous statistical data, protecting users' privacy is critically important. Adhering to data privacy is both a moral and legislative duty, becoming increasingly significant in today's information society.

- **Untrusted Scenarios**. In the client-server model's untrusted dialogue conditions, where neither party fully trusts the other, there is a need for mechanisms to ensure data privacy. This need may arise, for example, from using cloud services or other third-party platforms where users do not have complete control over their data processing.
- **Utilization of Fingerprinting**. A device's digital fingerprint represents unique identification information that can be used to link anonymous data across different sessions or steps in a dialogue. Relying on digital fingerprints can yield valuable statistical insights, but it is essential to ensure the anonymity and privacy of the fingerprints' owners.
- **Local Differential Privacy**. The LDP methodology allows for the collection of aggregated statistical data with minimal disclosure of sensitive information. This problem explores the application of this methodology for data entropy assessment, opening new possibilities for privacy preservation in untrusted scenarios.

Collectively, the issue is relevant due to the need to collect anonymous statistical data, link data using digital fingerprints without disclosing the owner's information, and assess entropy in untrusted client-server dialogue scenarios within the LDP framework. Solving this problem will achieve a balance between utilizing valuable information and protecting user privacy, which is crucial in modern data processing.

4 Device Digital Fingerprint

Websites often need to track visitors for various reasons, such as maintaining user sessions or implementing shopping cart functionality. The traditional method of tracking a user's identity is based on cookies, but in recent years, cookie technology has been revealing more and more problems. For instance, many websites misuse cookies for advertising purposes. These issues have led to growing mistrust towards cookies, prompting many people to install cookie-cleaning extensions or simply use private browsing modes. Concurrently, the technology of capturing digital fingerprints of devices or browsers has been gradually developing and is becoming the new primary technology for tracking users. Let's focus mainly on working with browsers. A browser fingerprint is a collection of all the feature information that can be gathered through the browser, but feature information does not include data filled in and sent by the user. Digital browser fingerprints depend solely on the uniqueness of the device itself. Thus, even in the case of encrypted, anonymous, mobile, and even cross-domain networks, it can be identified. Modern browsers are very complex, with each component having different characteristics, and these characteristics combine to form a unique browser fingerprint.

The ultimate goal of browser fingerprinting is to track a unique user entity. Therefore, obtaining high-entropy, persistent, and preferably cross-browser characteristics of digital fingerprints is the main direction of many research efforts in the field of browser fingerprinting. The table below (see Table 1) summarizes the characteristics of various methods for obtaining digital fingerprints in a browser.

Table 1. Characteristics of methods for obtaining digital prints in a browser

Method of obtaining	Peculiarities
JavaScript-based Fingerprint	Utilizes JS functions to call various APIs for information gathering
CSS-based Fingerprint	Can be used to parse CSS strings if the user has disabled JS usage
Canvas-based Fingerprint	Characterized by high entropy and great reliability
Hardware Survey Fingerprint	Most of these algorithms require actions to be taken with measurable results, which are used as the fingerprint
Audio API Survey Fingerprint	Almost identical to the previous point
Browser Plugins Analysis Fingerprint	Involves analyzing installed browser extensions, with the list effectively serving as the fingerprint
Other Methods	Often these are exotic methods based on measuring the performance of different tasks on the device and in the network

Using a similar set of identifying features, it is possible to compile an approximate device fingerprint, as reflected in the following table (see Table 2).

Table 2. Approximate (Incomplete) Contents of a Browser's Digital Fingerprint

User-Agent	Mozilla/5.0 (Windows NT 10.0; Win64; ×64) AppleWebKit/537.36 (KHTML, like Gecko) Chrome/92.0.4495.0 Safari/537.36
Accept	text/html, application/xhtml+xml, application/xml; q = 0:9, image/webp; q = 0:8
Accept-language	ru-RU, en-US; q = 0:5
IP	84.205.22.116
Platform	Windows
Vendor	Google Inc.
appName	Netscape
Product	Gecko
cookieEnabled	True
Local time	Mon Feb 03 2024 09:57:32 GMT+0300
Resolution	1920 × 1080
WebGL vendor	Google Inc.
...	...

The digital fingerprint of a browser is complex, with different components having varying probabilities of occurrence. The uncertainty of this information can be described and measured using standard methods, the most obvious of which is the use of Shannon entropy, as suggested by the "founder" of research on browser digital fingerprinting in his work [27]. The author proposes the following line of thought: suppose there exists an algorithm for forming a browser's digital fingerprint, $F(x)$, which is analogous to a hash function. For each input browser fingerprint x, there exists a unique result from the mechanism's operation $F(x) = f_n, n \in [0, 1, \cdots, N]$.

The probability of occurrence of each result f_n is equal to $P(f_n)$. Subsequently, one can obtain the corresponding measure of uncertainty or self-information:

$$I(F(x) = f_n) = -log_2(P(f_n))$$

Next, we can round the result up to determine how many bits of information are needed to represent the information. Subsequently, the information entropy of the distribution of browser digital fingerprints is determined by the following formula:

$$H(f) = -\sum P(f_n) log_2(P(f_n))$$

Since the digital fingerprint of a browser consists of both hardware and software components, we can similarly define methods for identifying an individual browser component, for which the following will hold:

$$H_s(f_s) = -\sum P(f_{n,s}) \times log_2(P(f_{n,s}))$$

If browser components are independent of each other, their information entropy can be linearly increased, but this is often not the case. Components in most browsers are usually interconnected. For example, the Edge browser is more commonly associated with the Windows system, while the Safari browser is often tied to the iOS system. Therefore, it is appropriate to use conditional distributions for some components. Thus, the uncertainty can be expressed as follows:

$$I_{s+t}(f_{n,s}, f_{n,t}) = -log_2(P(f_{n,s}|f_{n,t}))$$

Within the scope of this article, it would be highly beneficial to consider a time-based characteristic of differences called discrepancy decay. Discrepancy decay refers to the probability that an object will change the value of attribute s over time Δt. This probability is denoted by $d^{\neq}(s, \Delta t)$.

Many events can lead to changes in a browser's digital fingerprint. In the case of the described and most logical algorithm, these events include, for example, updating the browser, updating a plugin, disabling cookies, installing a new font or an external application that includes fonts, connecting an external monitor that changes screen resolution, and so on. The author of the study [9] notes that among the users of the Panopticlick site database, the frequency of digital

fingerprint changes among returning users who accept cookies was very high: 37.4% of users visited the site more than once, and over time (within a 2–3 week period) they acquired a new digital fingerprint for their browser. By applying certain heuristic algorithms, it is quite possible to accurately identify minor changes in the browser configuration or the used device and find in the database the "previous version" of the digital fingerprint [27,29], thus ensuring device/browser recognition up to 99.5%, according to developers' claims.

5 Local Differential Privacy

The concept of Local Differential Privacy (LDP) [25,26] was proposed relatively recently as a stricter method within the differential privacy framework for preserving the confidentiality of personal information. LDP is based on the assumption that the data collector or central server cannot be trusted. In this context, each participant in the information process locally applies a differential privacy mechanism to their original data, leading to the creation of a modified version of these data. These modified data are then transmitted to an untrusted server, which acts as a collector or aggregator of data. Utilizing the modified data from all participants, the server calculates predefined statistics and publishes the statistical results. With its advantages, LDP was extensively researched and applied in industry soon after it was proposed.

There are several modern applications for the practical deployment of LDP for private statistical data collection, so LDP is used by hundreds of millions of people every day. For instance, Google's RAPPOR system [13] is based on the principle of random response and Bloom filter to implement a privacy-preserving data collection setting for mass Chrome users. This is the first and purely client-side practical solution for privacy protection that no longer requires the participation of a trusted third party and takes control of user data into its own hands. Apple announced [14] that LDP had been deployed in the iOS system, as documented in a patent application and research paper. The method is based on LDP with other techniques, including the use of Fourier transform to filter information and special subsampling methods to reduce data dimensionality.

The collection of telemetry data within the LDP framework was implemented by Microsoft in Windows 10, which uses histograms to collect data about systems and applications over time [15]. Additionally, Samsung [16] has also explored LDP technology, but it remains unclear whether it has been applied in practice.

Thus, one of the still promising and popular approaches is not to collect raw data at all. This approach was first used by Google for collecting statistics in the Chrome browser. Their system, named RAPPOR, is based on the implementation of the famous Warner's randomized response technique [17]. The randomized response works as follows: when a user wants to send a potentially sensitive piece of information to the server (for example, the answer to the question "Do you use Chrome?"), a virtual coin is "flipped" first, and if the coin lands on "heads," a random answer is returned - calculated by "flipping" another coin. Otherwise, an honest answer is sent.

The server collects responses from the entire sample of users and (knowing the probability with which the coin lands on "heads") adjusts to the existing level of "noise" to calculate an approximate answer for the truthful response. Intuitively, the randomized response protects the privacy of individual user reports because an answer "yes" could mean either "Yes, I use Chrome" or simply be the result of random coin tosses. Formally, the randomized response does indeed provide differential privacy, with specific guarantees that can be adjusted by regulating the characteristics of both the coin itself and the methods of "flipping".

Google, in its RAPPOR system, applies this relatively old technique and transforms it into something more powerful. Instead of simply answering one question, the system can compile a report on a complex vector of questions and even return complex answers, such as strings - for example, what homepage is set in your browser. This is achieved by first passing the string through a Bloom filter - a sequence of bits generated using hash functions in a very specific way. The resulting bits are then mixed with noise and summed up, with the answers being reconstructed through a rather complex decoding process. Unverified information suggests that Apple, in turn, describes and utilizes differential privacy as "using hashing, subsampling, and noise addition to enable crowdsourced learning while keeping individual user data completely private," reminiscent of the previous approach.

Furthermore, after such complex manipulations on the server side, each user is included in a certain cohort, and all standard statistics are performed exclusively by cohorts, reliably masking the data of a specific user among a mass of others. This approach closely resembles the methods used in the concept of k-anonymity.

There have been several reviews of existing ideas and technologies in the field of LDP that have emerged over the past few years. However, the rapid development of new approaches and the emergence of fresh ideas require constant attention to this topic. Similarly, and at the same speed, new possibilities related to the use of previously unconsidered technologies in connection with LDP, such as cryptography, emerge. The main mechanisms are described in the table (see Table 3).

Table 3. Mechanisms for altering or adding noise to data under LDP conditions

Mechanism	Advantages	Shortcomings	Mistake
Randomized response	Good scalability, low data processing and transmission costs	Only categorical data	$O(1)$
Laplace	Good scalability, low data processing costs (limited to noise calculation only)	Only numerical data, limited applicability	$O(\sqrt{N})$
Distortion-based	Dosing the size of information loss	Only for low-dimensional data, additional costs for "noising" data	$O(1)$
Compression-based	Control over the extent of information loss	High computational complexity for data compression and transmission, additional costs for data compression and "noising"	$O(1)$

6 Information Leaks

Research in establishing metrics applicable to the use of LDP is highly relevant. The foundations of modern approaches to accounting for privacy leaks were developed in a series of works [30,31], and subsequent research in various contexts using many different measures to ensure confidentiality. For example, differential privacy was defined in its centralized version in the context of database confidentiality to guarantee that the participation of no single individual could be disclosed based on the output of a function computed on the database (i.e., ensuring membership confidentiality). Later, in the case of differential privacy in its local version, the idea evolved into a concept where, broadly speaking, the goal is to provide equal plausible deniability for all possible values of a random variable. Concurrently with these developments, a wide range of confidentiality measures aimed at measuring the dependency between two random variables X (input) and Y (output) was proposed and studied in information theory literature. Up to now, and still, the prevailing approach to solving privacy problems has been to start with a specific definition of privacy, explore all the circumstances stemming from this definition, and attempt to develop and iteratively optimize mechanisms that guarantee a certain level of privacy and associated utility. Alternatively, one could start by defining a threat model in which an adversary with explicitly described capabilities pursues a specific goal and examines the system's vulnerability as a result of this model. That is, it involves narrowing the field of study, which suggests a significant easing of work for researchers.

The advantages of this approach can be described as follows:

- We can clearly formulate our assumptions about the capabilities of adversaries;
- We can define the concept of privacy in accordance with the threats;

– It becomes possible to develop measures to ensure privacy and objectively discuss them.

Intuitively, it may be understood that a leak is the volume of information obtained by an adversary as a result of observing the outcomes of a mechanism's operation. Following the assumptions of the authors [30], it seems natural to define this as the difference between the uncertainty regarding the input data before observing the output data and the remaining uncertainty afterwards:

$$Information\ Leak = Initial\ Uncertainty - Remaining\ Uncertainty \quad (1)$$

The question arises as to how to measure information and what can be considered as uncertainty. In relation to Eq. 1, entropy is classically measured in bits, and the initial uncertainty is defined as the minimum entropy of $X, H\infty(X)$, for example, Rényi entropy [32], obtained when $\alpha = 1$. As for the uncertainty remaining after observation, it would be natural to use the conditional minimum entropy of X given Y. Let's make some necessary definitions:

Assume all random variables are discrete and finite. Capital letters will be used to denote random variables, for example, X. Sets are denoted by uppercase letters, for instance, χ represents the alphabet of X. We use P_X to represent the probability distribution of X, and $supp(P_X) := x \in X : P_X(x) > 0$ to represent the support of P_X. If n is a positive integer, then we use $[n] := 1, \cdots, n$ to describe the set of all natural numbers ranging from 1 to n. Additionally, $log(\cdot)$ will be used to denote the natural logarithm.

For random variables X and Y, we will use $P_{Y|X}$ to denote the conditional probability of Y given the random variable X. Throughout this article, we use X to represent some data containing confidential information (i.e., data of a single user, statistics, or some secret symbol), the random variable $P_{Y|X}$ to represent the private mechanism responding to queries about X, and Y to represent the responses to public queries.

Next, we may be interested in quantitatively assessing the leakage under a given protocol, i.e., the amount of information about the input data that an adversary can learn by executing the protocol and observing the resulting output data.

Before launching the private protocol, the probability of correctly guessing the value of x depends only on the prior distribution of X, and therefore, a conventional rational adversary would assume that the most probable value of x, called the prior probability of a correct guess, would be the value of x that has the maximum prior probability $PR(X) = max_x(P_x)$.

Many authors, based on definitions by Smith [31], propose the following definition of conditional entropy:

$$H_\infty(X) = -log(PR_o(X))$$

Thus, based on this definition, one can define leakage as follows:

$$L(X;Y) = H_\infty(X) - H_\infty(X|Y) =$$
$$-log(PR_o(X)) + log(PR(X)) = log(PR(X)/PR_o(X))$$

Interestingly, the greatest leakage occurs in the case of a uniform distribution [30].

Many studies in this field have expanded the model described above [33–36], using the concept of leakage $L(X;Y)$ as a tool for quantitatively assessing privacy. The results of these studies suggest that the maximum leakage calculated in this way is a convenient measure of privacy with a reliable definition, which can be used in a variety of different scenarios. However, one of the apparent limitations of such a definition is that the maximum leakage is determined for the average result Y. Therefore, such privacy guarantees do not provide the ability to distinguish between individual possibilities of leaks based on their outcomes.

7 Impact of Features on Privacy Leakage

Within the framework of this article, approaches to assessing privacy leakage associated with identifying features of digital device fingerprints are considered. Utilizing a dataset, each element of which includes identifying features listed in Table 2, the following assessment algorithm was developed:

1. **Definition of input data**: the dataset D consists of n elements, each incorporating identifying features F_1, F_2, ..., F_m.
2. **Calculation of entropy for each feature**: for each feature F_i, calculate its entropy $H(F_i)$ as a measure of uncertainty or diversity of feature values.

Algorithm 1. Calculation of entropy for each feature

```
function CalculateEntropy(F)
count ← map of (value → frequency)
for v in F do
    count[v] ← count[v] + 1
end for
total ← length of F
H_F ← 0
for each (value, frequency) in count do
    p ← frequency/total
    H_F ← H_F − p · log2(p)
end for
return H_F
```

3. **Analysis of mutual information**: for each pair of features F_i and F_j, calculate the mutual information $I(F_i;F_j)$ to assess the degree of their interdependence.

Algorithm 2. Analysis of mutual information

```
function CalculateMutualInformation(F, G)
H_F ← CalculateEntropy(F)
H_G ← CalculateEntropy(G)
joint_count ← map of ((f, g) → frequency)
for each pair (f, g) in zip(F, G) do
    joint_count[(f, g)] ← joint_count[(f, g)] + 1
end for
total ← length of F
H_FG ← 0
for each ((f, g), frequency) in joint_count do
    p_fg ← frequency/total
    H_FG ← H_FG − p_fg · log_2(p_fg)
end for
return H_F + H_G − H_FG
```

4. **Data aggregation**: using the obtained measures of entropy and mutual information, aggregate the data to obtain an overall indicator of privacy leakage through compositional information security measures.

Algorithm 3. Data aggregation

```
function AggregateData(measures)
result ← 0
for measure in measures do
    result ← result + measure
end for
return result
```

5. **Correlation analysis**: determine the correlation of privacy leakage relative to the number of identifying features in the dataset.

Algorithm 4. Correlation analysis

```
function CorrelationAnalysis(X, Y)
mean_x ← Average(X)
mean_y ← Average(Y)
numerator ← 0
denominator_x ← 0
denominator_y ← 0
for Each(x, y) in Zip(X, Y) do
    numerator ← numerator + (x − mean_x) * (y − mean_y)
    denominator_x ← denominator_x + (x − mean_x)^2
    denominator_y ← denominator_y + (x − mean_y)^2
end for
return numerator/√(denominator_x * denominator_y)
```

In this study, the input data were collected from 15 different, non-repeating devices using a variety of browsers. These initial data included unique digital fingerprints of each browser, incorporating information such as operating system version, installed fonts, screen resolution, and other browser data that could serve as identifying features.

To expand the dataset and increase its diversity, the initial data were artificially modified and augmented, allowing the generation of new variant digital fingerprints. As a result of this process, the total volume of data increased to 100 different digital fingerprints. Special attention was given to ensuring a high level of entropy during data generation to maximize uncertainty and complexity, which is critically important for privacy analysis.

Based on this enhanced sample, a study was conducted aimed at averaging privacy loss and analyzing the impact of the number of identifying features on the level of data leakage. The results were presented in a graph (see Fig. 1) that illustrates the nonlinear increase in privacy leakage as the number of features in the dataset grows. This analysis underscores the importance of careful data control and protection when working with large volumes of information and multiple identifying characteristics.

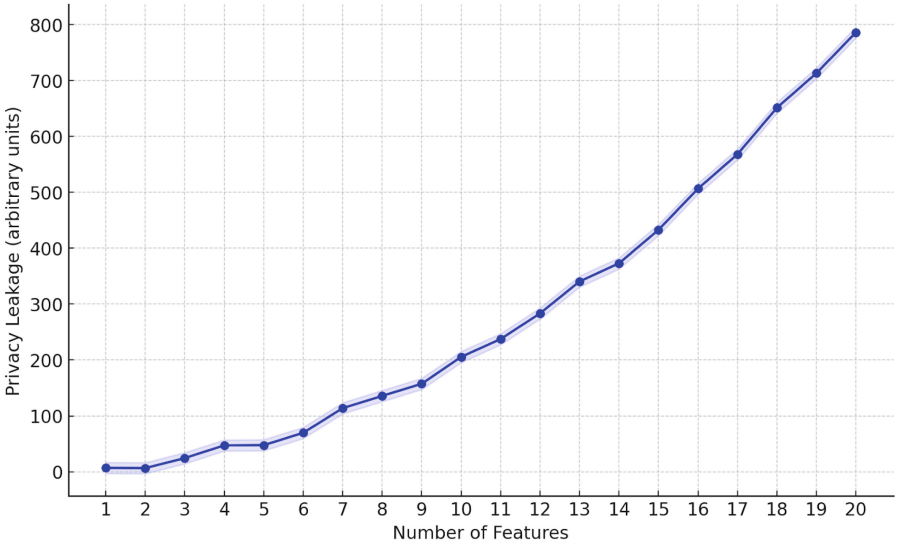

Fig. 1. Dependency of Privacy Leaking on Number of Features

In this case, privacy leakage increases quadratically as the number of features increases. This is because adding each new feature not only linearly increases the amount of information but also enhances the complexity of the interrelationships and combinations among features, leading to a more significant growth in

potential leaks. Such a conclusion underscores the need for stricter confidentiality measures when working with large datasets.

The graph displays deviations from the norm (highlighted in light blue), illustrating possible variations in privacy leakage due to random factors or changes in the data. This deviation could represent differences in leakage due to the varying effectiveness of implemented security measures or the specifics of data processing under different conditions.

8 Minimization Models

We may be interested in the fact that in many cases, a digital fingerprint is a kind of hash, the value of which is unstable over time and computed by various algorithms. Thus, a digital fingerprint can also be considered a random variable. Therefore, willingly or unwillingly, in the presence of a digital fingerprint, there may exist multiple databases or database fragments containing tuples with the digital fingerprint as a user identifier. These records can be formed either using Local Differential Privacy (LDP) technologies or without this concept. In this case, any fragment can be considered auxiliary (for the adversary) to the others (see Fig. 2).

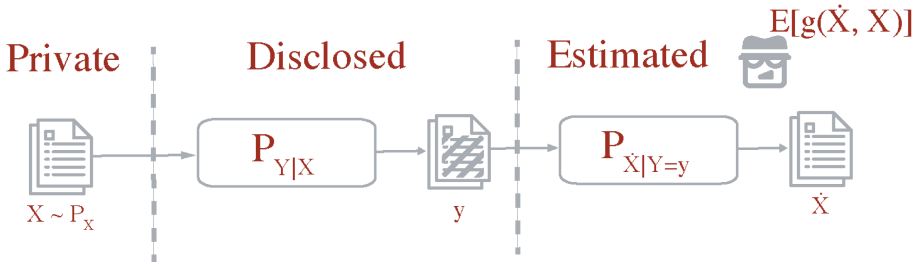

Fig. 2. Information Leakage Minimization Model

One can conceive an information leakage minimization model. Suppose we are given a random variable X with distribution PX, and by using the mechanism PY—X, we can add noise to these sensitive data. It's clear that in this case, it would be quite difficult for an adversary to construct a new estimate. The function's result will depend on the balance between data privacy and utility. In some instances, a compromise between these two aspects may be required.

Recalling the thesis about the utility of a DP algorithm degrading to zero when an adversary possesses external or auxiliary information, one might assume that in conditions of widespread use of digital fingerprints, it is necessary to move from classical definitions of differential privacy to some new definitions of privacy and utility that would allow for the evaluation of mechanism privacy. In doing so, of course, an attempt should be made to define the relationships of new algorithms with those algorithms already practically recognized as classic (see Fig. 3).

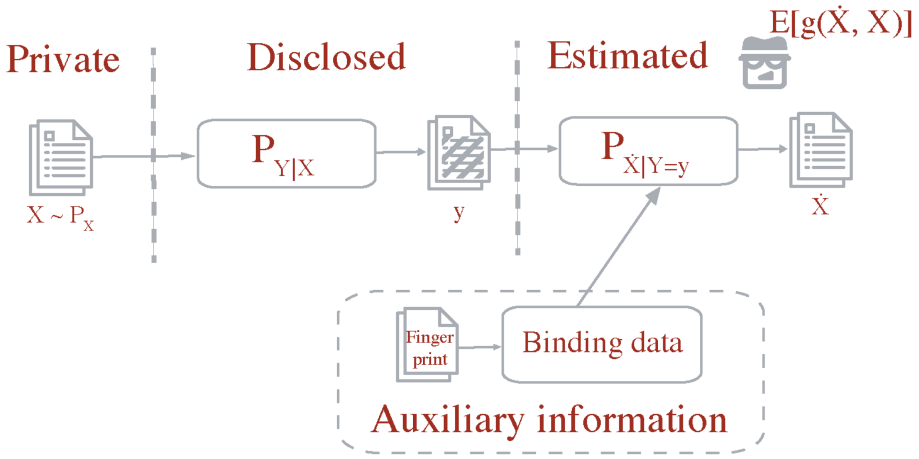

Fig. 3. Information Leakage Minimization Model Using Auxiliary Information

Let's assume X is a random variable representing some data containing confidential information. We'll keep X abstract to maintain generality. X could be a single data record obtained from an individual (local version of DP), X might represent an entire database containing confidential information (centralized DP), or X could be a secret symbol, such as a password (under potential side-channel attack conditions).

Next, suppose Y is the output of a randomized function with input X. For example, in the context of local DP, Y denotes the noised data of a single user, collected by an untrusted data server. In centralized DP conditions, Y might be some statistics (sum, average, etc.), computed from the database, and in side-channel conditions, Y could be some physical output data related to the input X, like delays between keypresses when entering a password. In all these scenarios, we are interested in answering the following question: how much information do we gain about X through observing Y?

9 Conclusion

This study focuses on exploring the capabilities of privacy leakage assessment in the context of an untrusted client-server dialogue within the framework of Local Differential Privacy (LDP). In the realm of collecting anonymous statistical data and utilizing device fingerprints, the issue of privacy becomes critically important.

The research is highly relevant as there is a need to process data in conditions of distrust between the client and the server, as well as to maintain the privacy and anonymity of users. The application of the LDP methodology allows for the minimization of potential privacy loss during data collection and analysis. This research contributes to the development of entropy assessment algorithms that

can be used for data aggregation and statistical indicator extraction without disclosing personal information.

The findings of this research can be applied in various fields, such as user behaviour analysis, big data processing, and decision-making based on statistical data. It is anticipated to explore algorithms and methods for ensuring privacy that can be implemented in real systems, thereby adhering to regulatory requirements and increasing user trust in the process of processing and using their data.

Research in this direction can make a contribution to the fields of data privacy and the processing of anonymous statistical data under conditions of untrusted client-server dialogue. The algorithms and privacy assessment methods developed within the LDP framework can provide a balance between the use of sensitive data and the protection of user privacy, contributing to the development of safe and trustworthy information processing in the modern information society.

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A New Approach to Managing Smart Environment Infrastructure Settings

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Abstract. The main problems of constructing and configuring of automation systems based on the "Smart Environment" technology come from the need of combination of heterogeneous software and hardware from various manufacturers in a single information space. The article focuses on the speech recognition method of setting up and training of the "Smart Ecosystem" using innovative artificial intelligence (AI) technology.

Keywords: Smart House · Smart Ecosystem · Smart Habitat · specialized software platform · natural user interface · speech recognition

1 Introduction

One of the significant factors of improving the quality of life of the population in modern conditions is the use of so-called "Smart Environment" technology, which, in the course of development, turns into a whole strategic direction of building habitat infrastructure called "Smart Habitat" (SH) or "Smart Ecosystem", consisting of elements of a "Smart System", IoT, etc. (Fig. 1) [1].

These elements of the "Smart System" can interact with each other by connecting via an internal network or switched via the global Internet. At the same time, there is increasingly a need to integrate not only different types of Smart System elements, but also those developed by different manufacturers, for example, smart lamps from Xiaomi and Philips HUE. In addition, owners (customers) of such installations increasingly have a desire, and sometimes a need, to manage them remotely using a computer, mobile device or voice assistant.

Recently, the most popular option is the ability to voice control not only individual devices, but also individual scenarios and extended scenarios as part of the "Smart Environment". This area has received especially active development with the appearance on the modern market of a large number of smart assistants such as "Alice" (a Yandex service), "Siri" (an assistant from Apple), "Google Now" (an assistant from Google), "Marusya" "(VK service)" "Salyut" (Sbera service), Alexa (Amazon) and others [2].

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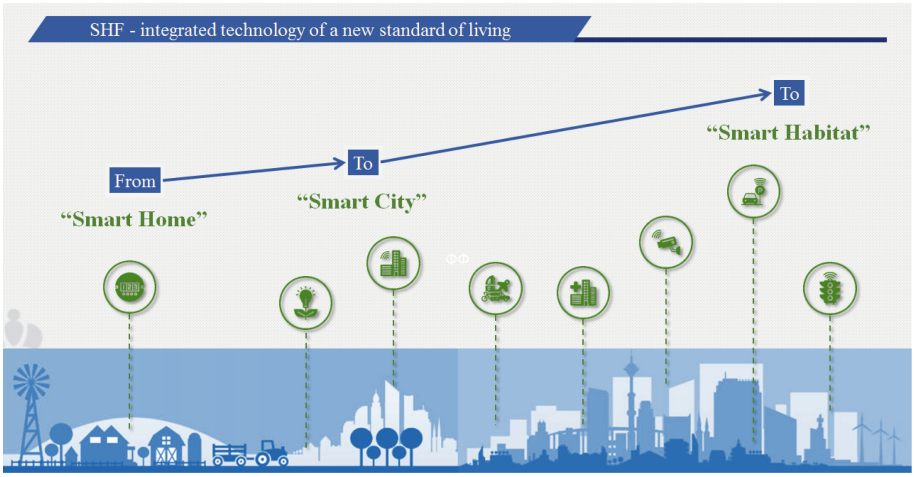

Fig. 1. SH development

The main prerequisite for voice control was the use of a user-familiar method of interaction between a person and a computer, implemented using a natural "communication" interface, which implies the use of innate means by a person such as gestures, voice, gaze. It should be noted that the most natural means of interaction for a person is speech, therefore the speech user interface has a number of advantages: minimal training time for the user to use the system, simplicity and high speed of generating requests to the system. This was the reason that made it possible to actively use the speech user interface in Smart Systems to control devices and scenarios.

And if the issue of managing fragments of SH ("Smart Home", "Smart Building", "Smart Office", "Smart Enterprise", etc.) is gradually finding its niches thanks to various innovative solutions, then the issue of customization and further training or reconfiguration (modernization) "Smart systems" is still a kind of "magic" of a narrow circle of specialists. Only these specially trained employees can make the necessary changes from the simplest to the most complex reconfiguration in the work of the SH, while spending serious material and time resources, including the Customer, not to mention various inconveniences and additional expenses.

The approach outlined later in the article proposes not only a new approach to the issue of setting up Smart systems, but also using the capabilities of AI for innovative training and subsequent equipment modernization in order to increase the efficiency of managing intelligent components of not only the "Smart Home", "Smart Building" etc., but also SH. At the same time, the novelty of the proposed approach consists primarily in carrying out voice tuning of the training system, as well as the possibility of subsequent modernization of the control system of the fragments of the SH.

2 Analysis of the Problems of Installation and Modernization of "Smart Systems"

"Smart Home", as a separate fragment of the "Smart Ecosystem", is a fully automated set of equipment that allows you to manage various household processes. The apartment owner controls the equipment using a remote control, an application on a mobile phone or using voice commands. The system may include household appliances, video and audio equipment, devices for controlling the microclimate in the room, etc. A necessary option is also control over the security system: surveillance cameras and alarms. In addition, a "Smart Building" system with additional capabilities is installed in private homes: control of water supply, heating, gas supply, etc.

And if all systematic steps for planning, design, installation and development of "Smart Systems" are defined and relatively unified, then most of the issues related to configuration, expansion of functionality, training and development for further operation remain open [3]. The combination of these issues develops into a serious problem for the following reasons:

1. Lack of a generally accepted concept for using the "Smart System" at the initial stage of its installation. The Customer (User), despite the great desire to explore all the possibilities and methods of using "Smart Things", various IoT, etc. in his environment usually does not fully understand the practical orientation of the "Smart Environment". He needs time both to get used to it and to acquire the necessary skills for further and future use.
2. Constant updating and expansion of the fleet of sensors and devices (capabilities of the "Smart System") and, accordingly, changes in the software of "Smart Systems" leads to an increase in the number of installed sensors and devices (capabilities of the "Smart System") about which the Customer (User) is often not aware This circumstance necessitates modification (if we are not talking about some serious reconfigurations) of the software and hardware and customizing it to your requirements.
3. Reluctance or impossibility due to temporary or financial difficulties to call specialists with sufficient professional skills to carry out highly qualified tuning work. Obviously, employees of Smart Systems companies will not refuse the request, but their work may be carried out at an inconvenient time for the customer, postponed due to workload for a long time, etc. What if you need to perform some simple setup operation, etc.?
4. The presence of heterogeneous systems from different manufacturers, which causes great inconvenience in managing these devices and systems as part of a single information space, not to mention the possibility of their uniform configuration or training.
5. The possibility of leaving (at best, temporary) a particular brand for technical reasons or other reasons, as well as ceasing support for outdated equipment. A striking example of this fact is the inability to connect Redmond's "Smart Appliances" to the Sky smart platform in November 2023. Despite the fact

that the reason was the debt of suppliers who had not paid for the corresponding licenses, customers were faced with malfunctions of the purchased devices. This problem was solved only in 2024. At the same time, the developers of the "Smart Home" components "Insteon" simply turned off their servers and the equipment lost its smart functions, and then stopped responding to control commands. In December 2023, the Yandex Smart Home did not work for about a day due to an accident on the Alice servers. The list of similar situations can be continued, but you should understand that if, due to a failure on the server, the light in the toilet stops turning on, this is not a big problem. But if, due to a sudden shutdown, the alarm signal from the security or smoke sensor is not received, the situation could turn into a disaster [4].

And this is not a complete list of problematic issues related to setting up and training Smart Systems. In order for the slogan "Welcome to the world of "Smart Systems", where technologies make our lives more comfortable and convenient" not to sound so openly provocative or frightening, but to demonstrate a real approach to the operation of the "Smart Environment"", this article will present results of a study to create a unified platform with the ability to integrate a training system based on an intuitive natural interface - a speech method of entering information.

3 Development of a Specialized Software Platform

To create our own prototype of a specialized software platform (SSP), it was carried out in 2 stages:

Stage 1 - research and analysis of methods for constructing an SSP that combines fragments of heterogeneous "Smart Systems" from various manufacturing companies in a single information space.

Stage 2 - analysis of alternative ways of teaching "Smart Systems", taking into account the features of speech input.

At stage 1, the main attention was paid to the problems of functioning of the "Smart System" on a cloud-based and local (on-premise) resource. How does the local version of the Smart Environment differ from the cloud version? Systems from Yandex, Google, Apple and Xiaomi, etc. rely on cloud services. And they, as it turns out, can easily disconnect users based on geography, be attacked by hackers, or stop working for some other reason.

Therefore, to build an SSP, the option of building a "Smart Environment" on a local resource was proposed. The "on-premise" solution has a number of significant advantages compared to the "cloud-based" option. An important advantage is the ability to control the information flow circulating in the SSP, because information is stored on a local server (within a controlled area), and, therefore, the access control table, audit log and other security requirements are controlled, while cloud solutions cannot guarantee the safety of information due to the risks of DDos attacks, etc. The "on-premise" option has advanced infrastructure settings for the Customer's needs (flexibility), the ability to operate in real time

(a sensitive parameter for SSP) and compliance with information security requirements (anonymization of personal data, compliance with requirements for the safety of corporate and other information). At the same time, systems in the "on-premise" version can receive commands from the User via the Internet, but all devices interact with each other in the "Smart Environment" via a local network.

The characteristics of the local server must be no lower than:

- CPU: Core i5-13600KF or Ryzen 5 7600X.
- RAM: minimum 8 Gb DDR4, Memory frequency: 2666M or more powerful.
- HDD for datasets: 1 TB or more.
- SSD: at least 128 GB.

The configuration is determined based on the need to support speech input.

There are several popular ready-made open source home automation platforms. Almost all of them allow you to configure devices and Smart Environment scenarios through user-friendly applications or a web interface. The list of the most common systems should include:

- "Home Assistant" is the most popular system, it is easiest to learn with instructions.
- "OpenHAB" is a somewhat "overcomplicated" system for creating scripts; programming skills are required.
- "Domoticz" is a fairly functional system, but the interface looks outdated.
- "ioBroker" - slightly less compatible with various systems than Home Assistant.
- "Node-RED" is a difficult system to master, as it is based on visual programming.
- "Apple HomeKit" is a home automation system where control centers are produced directly by Apple, and other devices can be produced by third-party manufacturers, but must undergo mandatory certification. Along with high quality and security, and the use of Siri for voice control, the main disadvantages include cross-platform issues and extremely high cost.
- "Samsung HomeKit" includes everything you need - from control centers to sockets, switches and light bulbs with the ability to connect devices from other manufacturers through the SmartThings gateway, using voice control with Google Assistant and Amazon Alexa. But at the same time, the necessary set of components for the minimum version of a "Smart Home" is practically absent.

Among the reviewed and tested systems, the "Home Assistant" (HA) is of greatest interest as a prototype of the proposed SPP, as a system that uses open source code as software (Fig. 2).

In addition, the feasibility of using this system follows from its following capabilities:

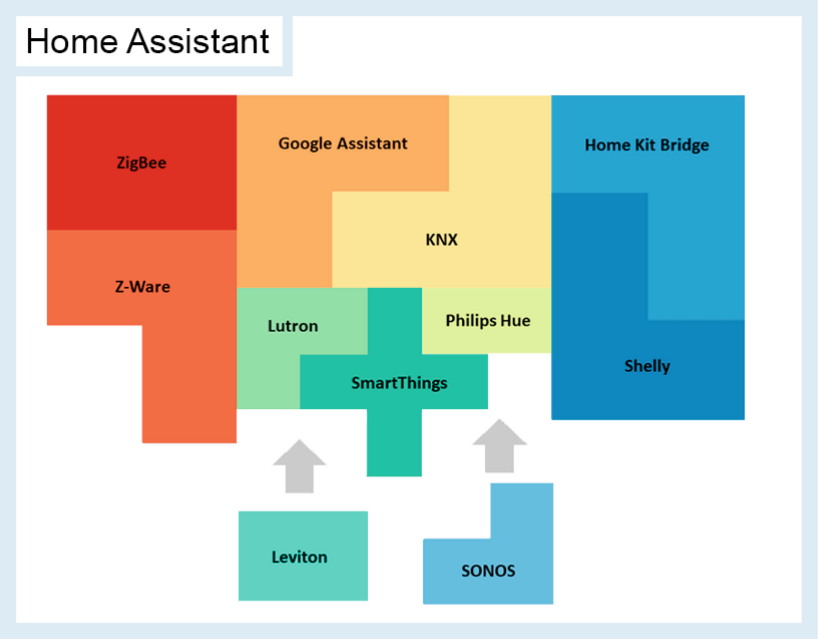

Fig. 2. Integration of heterogeneous systems into the Home Assistant platform

1. Support for devices from different manufacturers.
2. Implementation of complex automation scenarios with the ability to use voice control (assistants) and visualization via a web interface.
3. Setting up applications for managing "Smart Systems" via mobile devices and other types of IoT.
4. Supports major communication standards, including widely used Wi-Fi, Bluetooth, ZigBee and Z-Wave protocols.
5. Integration of security and fire alarm systems, access control systems (intercom communication systems) and video surveillance to organize a complex of technical security systems.
6. Using SQLite as a database with an interface based on SQLAlchemy and, as a result, supporting a fairly wide range of relational DBMSs, namely Microsoft SQL Server, MySQL, MariaDB, PostgreSQL and others. YAML syntax is used for configurations and settings. Although most integrations are configured through the user interface, some tasks require editing the main configuration file

At the same time, "Home Assistant" supports various installation options:

1. HA Operating System (recommended by the developer): installs the program as an operating program for working in home automation tasks, includes the kernel, the Supervisor function for managing the kernel, a set of pre-installed plugins for integrating devices and accessing services.

2. HA Core: manual installation of the kernel using the Python virtual environment (suitable for experienced users), gives full access to the platform, requires minimal knowledge of the operating system and the ability to work with the Python environment and the command line.
3. HA Operating System is HA Supervised: installing the platform kernel with the Supervisor function in manual mode (suitable for advanced users), provides the most complete control over the system, but in this case only works with Linux.
4. HA Container: installing the kernel in Docker containers.

The HA software platform includes integration for connecting Google Assistant and Amazon Alexa, which makes the use of voice assistants possible. A problem for the user may be the monolingual interface (English only) for the Amazon assistant and not always correct processing of information from Google devices. In this case, in the context of building a "Smart Ecosystem", it is advisable to use a version of the HA platform with manual installation of the kernel, which will allow creating the software basis for the SPP prototype. Taking into account the open source code of the HA platform, the current question is to develop language service code in accordance with the documentation on the language API (Application programming interface) for the operation of voice assistants when interacting with the platform. The solution being developed is necessary to create a fully functional SPP with the subsequent integration (stage 2) of the capabilities of speech customization and training of the "Smart Environment" into it.

4 Justification of the Speech Method of Entering Information for the "Smart Environment"

Studies of various options for entering information into electronic devices and systems (text and voice input were compared) have shown that for a person, voice or speech input is a much more effective input method than typing on a keyboard. Therefore, it is not surprising that humanity has long been interested in the issues of interaction with computing and other intelligent electronic devices through speech.

The theoretical foundations for constructing a speech recognition system (SRS) are reflected in the classic works of L.E. Baum and his colleagues [5,6], where it appeared as part of solving the problem of creating a signal model, as well as extracting information about the source. Later, the idea of using the mathematical basis of Markov chains for SRS was presented in the works on Hidden Markov Models (HMM) by L.R. Rabiner and E.I. Bovbel [7,8]. It should be noted that the HMM theory was chosen as the methodological basis for creating the SPP module, but its presentation of its provisions is beyond the scope of this study.

Modern trends in the development of IoT have demonstrated that the future belongs to a comprehensive user interface that allows using, in addition to vision,

various human senses, primarily hearing and speech. These assumptions are based on the following facts:

- speech is the most popular form of communication in the human environment;
- hands and eyes remain free, which makes the voice interface a priority;
- there is no need for direct contact during interaction, since the microphone and speakers can be located at a distance;
- modern software and hardware have achieved a fairly high level of accuracy in speech recognition.

Research has shown that when replacing the input method from classic to voice, information will be better processed by the user as time is saved when typing and further transmitting information in the form of text to its destination. At the same time, in both cases there are technical errors, but with voice input there are errors associated with incorrect recognition (about 5–7%), which often leads to an increase in input time (additional input of words, phrases, commands). In addition, as practice shows, voice input becomes the most effective solution when the query length is 2 words or more, but this usually requires a keyword [9].

According to statistical data, the promise of speech input is due to the following:

1. Voice queries are 3.7 times faster than traditional ones.
2. Quick input is usually equivalent to a quick answer, and users prefer voice search for the sake of speed.
3. Voice search is widely used in IoT. According to Stone Temple, about 60% of users searching on mobile devices use Voice Search.

Taking into account modern trends, the applied use of voice information recognition systems looks quite logical and relevant for organizing information input for setting up and training the “Smart Ecosystem”.

In terms of application, for integration into SSP it is planned to use an already developed and tested tool, the so-called speech recognition “engine” or Automatic Speech Recognition (ASR) with an available API for embedding ASR into software applications.

In modern conditions, ASR is increasingly used in various fields of development of science and technology, namely:

- Transcription and dictation. ASR is widely used for transcribing audio recordings when generating various types of reports, saving lecture material, etc. These operations allow you to quickly and accurately convert voice into text form to further simplify the process of data processing and analysis.
- Speech recognition in automated and guided vehicles, which allows drivers (operators) to control various functionality of these vehicles.
- Voice assistants and control systems of modern “Smart Ecosystems”. Here ASR is a key component of voice assistants “Siri”, “Alice” and “Google Assistant”, etc. where users interact with different types of IoT, ask questions, and control devices using only speech input.

Thus, the above analysis showed the possibility of using SRS as an alternative way of entering information into the "Smart Ecosystem" for setting up and further training its individual elements and the entire system as a whole. At the same time, a number of limitations and assumptions related to the peculiarities of the implementation of the SSP should be taken into account.

5 Application of Speech Methods of Teaching "Smart Systems"

It is worth noting that the speech control of the "Smart Ecosystem" has been successfully implemented both on the basis of individual "Smart Systems" such as "HDL", "Xiaomi", "Philips HUE", "Google", "Yandex" and others, and in the combined environment like "Home Assistant" [10].

A study of existing algorithms for setting up and further modernizing the settings (training) of the Smart Ecosystem showed that the set of control instructions and the dictionary of words used are deterministic.

Standard similar set includes:

1. A package of instructions, which includes commands to control the activation of Smart Ecosystem devices depending on user actions or logical conditions (time, lighting, temperature, etc.). For example, "Enable", "Disable", "Increase", "Decrease", "Close", "Open", etc.
2. A list of devices, which includes elements of the "Smart Ecosystem" that are subject to the instructions. For example, "Lamp", "Sensor", "Warm floor", "Radiator", "Air conditioner", etc.
3. A list of locations, which includes definitions of places where this activation must be implemented. For example, "Kitchen", "Living room", "Dining room", "Toilet", etc.

Thus, the complete composition of the phrase for setting (training) may look like this: "Turn on the lamp in the kitchen", while the instructions for issuing for execution or reconfiguration may include other conditions, but for the correct functioning of the system, all of them must be determined in advance.

The process of preparing for operation using SRS can be implemented on the basis of a chatbot, which, upon command, asks questions like "What to do and with what? Where to do it? or similar. After completing the input, this information is visualized and presented to the Customer (user) in a graphical interface for approval of the final version of the Smart Ecosystem management. This method of entering setup and training information is strictly defined. At the same time, it should be noted that currently the following innovations have appeared for voice input - queries have become longer, and the style of queries has become more conversational, there is more human speech in them. In this case, an alternative way of entering voice training information in free form is possible, which significantly affects the input process and the operation of SRS. Therefore, the mandatory presence of keywords will allow us to form the correct

basis for setting up the "Smart Ecosystem". In this case, the SRS software must analyze the "key" phrases to save and prepare for approval by the user.

In the process of developing the SRS, it is necessary to take into account protection from incorrect recognition and extraneous noise, "cut-off" of the beginning and end of the input, the mandatory use of keywords, the possibility of correction and return to repeated input, etc. Thus, the procedure for recognizing and forming a database (DB) of training commands should be as follows:

Step 1 - receiving sounds into the recognition software application;

Step 2 - processing the received audio signal, assessing the quality and eliminating interference;

Step 3 - highlighting signal sections containing speech training commands using keywords;

Step 4 - speech recognition in selected areas, followed by saving in the database;

Step 5 - testing and adjusting, if necessary, the training database.

According to the requirement for the need for the functioning of the SRS in a local version (without an Internet connection), it is proposed to consider the option of implementing speech input of educational information in the Python software environment (hereinafter referred to as Python).

The following libraries can be used for speech recognition [11]:

1. SpeechRecognition - provides support for multiple engines and APIs such as Google Web Speech API, Microsoft Bing Voice Recognition and IBM Speech to Text.
2. PyAudio - designed for audio input and output in Python, provides the ability to use a cross-platform audio I/O library.
3. DeepSpeech - is an open source voice recognition software system based on deep learning.

A number of research experiments were conducted to develop recommendations for the use of open source speech recognition systems.

To this end, five open source systems are considered: HTC, Kaldi, Julius, and RWTH ASR. The choice of these systems is based on the fact that they are currently the most frequently mentioned in modern research papers and are used by software developers [12–15]. The selected systems were compared in terms of such indicators as accuracy and speed of recognition, ease of use and internal structure.

The accuracy of the system was compared using the most common metrics [16]: Word Recognition Rate (WRR), Word Error Rate (WER), which are calculated using the following formulas:

$$WER = \frac{S + I + D}{T} \tag{1}$$

$$WRR = 1 - WER \tag{2}$$

where S - the number of word replacement operations, I - the number of word insertion operations, D - the number of operations to delete words from the recognized phrase to get the original phrase, T - the number of words in the original phrase and is measured as a percentage.

In terms of recognition speed, the comparison was carried out using the Real Time Factor, an indicator of the ratio of recognition time to the duration of the recognized signal, also known as the Speed Factor (SF). This indicator can be calculated using the formula:

$$SF = \frac{Treg}{T} \tag{3}$$

where Treg - the time of signal recognition, T - its duration and is measured in fractions of real time.

All systems were trained using the WSJ1 (Wall Street Journal 1) speech corpus, which contains about 160 h of training data and 10 h of test data representing excerpts from the newspaper "Wall Street Journal". This speech corpus is usually taken for training purposes and includes recordings of male and female speakers in English.

After conducting the experiment and processing the results, the following table was obtained (Table 1).

Table 1. Results of comparison in accuracy and speed

System	WER	WRR	SF
HTK	19,5	80,5	1.4
Kaldi	6.6	93.4	0.6
Julius	23.2	76.8	1.4
RWTH ASR	15.4	84.6	3.8

At the same time, the accuracy and correctness of the study is confirmed by the fact that the results obtained are similar to those obtained when testing these systems on other speech corpora, such as Verbmobil 1, Quaero, EPPS [12,17,18].

To compare the structures, the system implementation language, algorithms used in recognition, input and output data formats and the internal structure of the software implementation of the system were selected as criteria, which is reflected in the tables (Tables 2, 3).

From the point of view of usability, the following indicators were considered - support for various software and hardware runtimes, support for many natural recognition languages, interface characteristics, availability of documentation, license restrictions. The results are presented in the following tables (Table 4).

During the experiment and subsequent analysis, the Kaldi system was selected. Which shows the best recognition accuracy of all the systems under

Table 2. System implementation languages and their structure

System	languages	structure
HTK	C	Modular, in the form of utilities
Kaldi	C++	Modular
Julius	C	Modular
RWTH ASR	C++	Modular

Table 3. Algorithm comparison results

System	Feature extraction	Acoustic modeling	Language modeling	Recognition
HTK	MFCC	HMM	N-gramm	The Viterbi algorithm
Kaldi	MFCC, PLP	HMM, GMM, SGMM, DNN	FST	Two-pass forward-reverse algorithm
Julius	MFCC	HMM	N-gramm, Rule-based	The Viterbi algorithm
RWTH ASR	MFCC, PLP	HMM, GMM	N-gramm, WFST	The Viterbi algorithm

consideration (WER = 6.6) and the second recognition rate (SF = 0.6). In terms of the algorithms and data structures provided for speech recognition, this system is a leader, as it provides the largest number of modern approaches used in the field of speech recognition, including the use of neural networks.

In addition, it allows you to use a variety of algorithms to reduce the size of the acoustic features of the signal, and, accordingly, increase the performance of the system. Kaldi is written in the C++ programming language, which has a

Table 4. The main indicators for SRS

System	Supported OS	Languages	Interface	Documentation	License
HTK	Linux, Mac OS, FreeBSD, Windows	English	Console, API	Comprehensive documentation	HTK
Kaldi	Linux, FreeBSD, Windows	English	Console	Detailed online documentation	Apache
Julius	Linux, Mac OS, FreeBSD, Windows	English, Japanese	Console, API	Comprehensive documentation	BSD like
RWTH ASR	Linux, Mac OS	English	Console	Not detailed documentation	RWTH ASR

positive effect on the speed of the system, and has a modular structure, which makes it possible to easily refactor the system, add new functionality, and correct existing errors. From the point of view of ease of use of Kaldi, it is necessary to note the availability of detailed documentation. The system is cross-platform, but provides only a console interface, which makes its integration into third-party applications difficult, but real. By default, this system supports only English (there are possibilities to connect other languages) and is distributed under a completely free Apache license, which allows it to be integrated into a commercial product without disclosing its code.

To build the SPP, you need to install Python v.3.8, the PyAudio = 0.2.11 and Vosk = 0.3.1.2 libraries, where Vosk is a stand-alone tool for speech recognition with open source code and a set of a large number of language models. When working with the Vosk model, the sampling frequency must be correct (a model with a large number of recognition languages supports a frequency of 8000, therefore, data from the microphone must be read at the same frequency).

It should be noted that the Vosk model functions correctly in the absence of noise, so it is necessary to either remove noise effects and extraneous sounds (there are a number of methods developed for this) [19], or use an alternative model that does not require preliminary cleaning from noise interference.

To significantly improve the speech potential of the "Smart Ecosystem", it is necessary to use the capabilities of AI-based technologies, given that the Kaldi application option involves connecting neural networks.

6 Option to Build a "Smart Ecosystem" Using Speech Input Technology for Control and Configuration

Taking into account the analysis of the options for building "Smart systems" and a number of research experiments, a block diagram of 4 software components (SC) is proposed (Fig. 3).

Thus, the proposed CPP includes:

1. SC "INFORMATION INPUT AND RECOGNITION" consisting of modules:
   - Data entry module - getting sounds into a recognition software application;
   - Data Preprocessing module - processing of the received audio signal, quality assessment and elimination of interference, removal of low-quality data, missing values, sound distortion of emissions);
   - Data Recognition module - (allocation of signal sections containing speech training commands using keywords - speech recognition in selected areas, followed by saving in the database.
2. SC "ORGANIZATION OF INFORMATION STORAGE (DB)" consisting of modules:
   - Equipment Reference - designed for storing a list of equipment with settings;
   - Command Reference - designed to store a list of configuration commands;

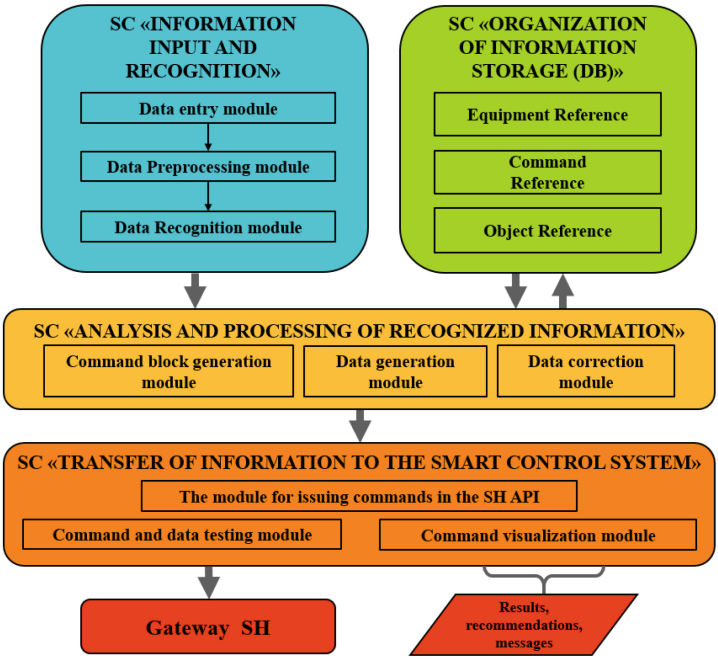

Fig. 3. Block diagram of organizing speech input into the "Smart Ecosystem"

- Object Reference - designed for storing a list of objects with settings.

3. SC «ANALYSIS AND PROCESSING OF RECOGNIZED INFORMATION» consisting of modules:
   - Command block generation module - processing and analysis of the information received, compilation of team buildings;
   - Data generation module - checking the correctness of the names of objects, commands, and the installation position of equipment;
   - Data correction module - correction of distorted information, correction if possible, request for re-entry.
4. SC «TRANSFER OF INFORMATION TO THE SMART CONTROL SYSTEM» consisting of modules:
   - The command and data testing module - issuing commands to verify compliance;
   - The module for issuing commands in the Smart Environment API - issuing commands to configure the system;
   - Command Visualization Module - issuing commands for system configuration.

The proposed SSP has expansion points for connecting software modules with AI-based capabilities, but at the current stage of development, it is tentatively planned to implement only voice input with AI.

Among the many capabilities of artificial intelligence technologies in the field of SSP, AI voice assistant as software that applies artificial intelligence and natural language processing to interact with users through speech is the first to be highlighted. With the help of available libraries and tools, it is easy to set up an environment and create a voice assistant that will respond to user requests and perform various tasks.

In this case, AI voice assistant can be used:

1. To improve recognition accuracy when entering configuration and training commands into the "Smart Ecosystem" (reducing noise levels, identifying dialects and normalizing the sound level, checking for correctness of input and compliance with the configuration of the created "Smart System", etc.).
2. To transform the input stream to a unified standard and generate a unified control and training effect.
3. To expand the functionality of the training system for adjustments and prepare additional capabilities for the "Smart Ecosystem".
4. To develop recommendations for managing Smart Ecosystem devices.

This list can be continued, but it is necessary to understand to what extent we want to automate processes in the "Smart Ecosystem" and what resources we have at our disposal. Thus, the creation and use of an AI voice assistant is a promising project that can provide users with many new opportunities.

7 Conclusion

The research conducted by the authors of the article aimed to show the possibility for the Customer (User) to create for themselves a single "Smart Ecosystem".

The main problematic issues of constructing and configuring automation systems based on the "Smart Environment" technology with the possibility of combining heterogeneous equipment from different manufacturers in a single information space are considered.

This work proposes a sequence of steps and a set of technologies that make it possible to implement an SSP with the possibility of speech input of control commands for setting up and further training the "Smart Environment" installed on the object. The use of AI technology for training "Smart Systems" allows the customer to significantly expand the capabilities of their personal "Smart Ecosystem", as well as independently configure and subsequently train this system without serious professional training.

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Author Index

A
Akritidou, Ersaia 16
Alessandro, Sciullo 207
Arianna, Stimilli 114
Assumma, Vanessa 147

B
Balletto, Ginevra 241, 253, 283, 294, 309, 325
Barbieri, Sebastiano 147
Basbas, Socrates 16, 41, 54, 65
Belcore, Orlando M. 3
Bogdanov, A. 358
Bogdanov, Alexander 405
Borruso, Giuseppe 241, 283, 309
Bottero, Marta 147, 163
Botzoris, George 65
Bouhouras, Efstathios 41, 54
Busko, Ilya 369

C
Campisi, Tiziana 41, 54
Caprioli, Caterina 147
Chatzimatos, Pantelis 65
Comi, Antonio 79, 97
Congiu, Tanja 265, 294
Cristina, Becchio 207

D
Datola, Giulia 176
Dell'Anna, Federico 163
Dell'Ovo, Marta 225
Di Gangi, Massimo 3
Dik, Aleksandr 405
Dik, Gennady 405

F
Faedda, Sara 265
Fancello, Gianfranco 283, 294
Fountas, Grigorios 16

G
Garau, Chiara 265
Giannoudis, Vasileios 54
Giovanna, Fancello 207
Giulio, Cavana 207
Golovkina, Anna 343
Grivas, Christos 65
Gryllias, Ioannis 65

H
Hriekova, Olesia 97

I
Ioannidou, Andromachi 16

K
Kiyamov, Jasur 405
Koenta, Anastasia 54
Korkhov, Vladimir 369, 386

L
Ladu, Mara 241, 253, 294
Lorenzo, Bottaccioli 207
Luca, Lupini Pagliara 114

M
Marialisa, Nigro 114
Marta, Bottero 207
Masera, Gabriele 189
Matiushin, Iurii 369
Misani, Camilla 189
Mogilnikov, Dmitry 343
Monaci, Sara 163
Moschella, Marialuisa 129

N
Naseddu, Marco 283
Nikiforiadis, Andreas 65

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O
Oksuz, Tuna 176
Oppio, Alessandra 176, 225
Ozgur, Damla 176

P
Paganelli, Gabriele 189
Persico, Simone 163
Pezzagno, Michele 325
Pittau, Francesco 189
Plaisant, Alessandro 265
Podsevalov, Alexei 386
Podsevalov, Ivan 386
Polimeni, Antonio 3, 79

R
Richiedei, Anna 325
Rindone, Corrado 28, 129
Russo, Antonio 41
Russo, Francesco 28
Ruzhnikov, Vladimir 343

S
Sdino, Leopoldo 176
Sechi, Francesco 309
Shchegoleva, N. 358
Shchegoleva, Nadezhda 405
Sinatra, Martina 241, 283, 309
Soffiantini, Letizia 189
Stamatiadis, Nikiforos 65
Sugoni, Giorgia 189

T
Tesoriere, Giovanni 41
Toutzaris, Alexios 65

Z
Zalutskaya, N. 358