Osvaldo Gervasi · Beniamino Murgante ·
Chiara Garau · David Taniar ·
Ana Maria A. C. Rocha ·
Maria Noelia Faginas Lago (Eds.)

LNCS 14817

Computational Science and Its Applications – ICCSA 2024 Workshops

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

3 Part III



Springer

Lecture Notes in Computer Science **14817**

Founding Editors

Gerhard Goos
Juris Hartmanis

Editorial Board Members

Elisa Bertino, *Purdue University, West Lafayette, IN, USA*
Wen Gao, *Peking University, Beijing, China*
Bernhard Steffen, *TU Dortmund University, Dortmund, Germany*
Moti Yung, *Columbia University, New York, NY, USA*

The series Lecture Notes in Computer Science (LNCS), including its subseries Lecture Notes in Artificial Intelligence (LNAI) and Lecture Notes in Bioinformatics (LNBI), has established itself as a medium for the publication of new developments in computer science and information technology research, teaching, and education.

LNCS enjoys close cooperation with the computer science R & D community, the series counts many renowned academics among its volume editors and paper authors, and collaborates with prestigious societies. Its mission is to serve this international community by providing an invaluable service, mainly focused on the publication of conference and workshop proceedings and postproceedings. LNCS commenced publication in 1973.

Osvaldo Gervasi · Beniamino Murgante ·
Chiara Garau · David Taniar ·
Ana Maria A. C. Rocha ·
Maria Noelia Faginas Lago
Editors

Computational Science and Its Applications – ICCSA 2024 Workshops

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

Springer

Editors
Osvaldo Gervasi
Department of Mathematics and Computer Science
University of Perugia
Perugia, Italy

Chiara Garau
Department of Civil and Environmental Engineering and Architecture
University of Cagliari
Cagliari, Italy

Ana Maria A. C. Rocha
Algoritmi Research Centre
University of Minho
Braga, Portugal

Beniamino Murgante
School of Engineering
University of Basilicata
Potenza, Italy

David Taniar
Faculty of Information Technology
Monash University Clayton Campus
Clayton, VIC, Australia

Maria Noelia Faginas Lago
Department of Chemistry, Biology and Biotechnology
University of Perugia
Perugia, Italy

ISSN 0302-9743 ISSN 1611-3349 (electronic)
Lecture Notes in Computer Science
ISBN 978-3-031-65237-0 ISBN 978-3-031-65238-7 (eBook)
https://doi.org/10.1007/978-3-031-65238-7

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2024

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

If disposing of this product, please recycle the paper.

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).

Honorary General Chairs

Norio Shiratori	Chuo University, Japan
Kenneth C. J. Tan	Sardina Systems, UK

General Chairs

Nguyen Canh Thai	Thuyloi University, Vietnam
Osvaldo Gervasi	University of Perugia, Italy
David Taniar	Monash University, Australia

Program Committee Chairs

Beniamino Murgante	University of Basilicata, Italy
Chiara Garau	University of Cagliari, Italy
Ana Maria A. C. Rocha	University of Minho, Portugal
Bernady O. Apduhan	Kyushu Sangyo University, Japan

International Advisory Committee

Jemal Abawajy	Deakin University, Australia
Dharma P. Agarwal	University of Cincinnati, USA
Rajkumar Buyya	Melbourne University, Australia
Claudia Bauzer Medeiros	University of Campinas, Brazil
Manfred M. Fisher	Vienna University of Economics and Business, Austria
Pierre Frankhauser	University of Franche-Comté/CNRS, France
Marina L. Gavrilova	University of Calgary, Canada

Sumi Helal	University of Florida, USA & University of Lancaster, UK
Bin Jiang	University of Gävle, Sweden
Yee Leung	Chinese University of Hong Kong, China

International Liaison Chairs

Ivan Blečić	University of Cagliari, Italy
Giuseppe Borruso	University of Trieste, Italy
Elise De Donker	Western Michigan University, USA
Maria Noelia Faginas Lago	University of Perugia, Italy
Maria Irene Falcão	University of Minho, Portugal
Robert C. H. Hsu	Chung Hua University, Taiwan
Yeliz Karaca	University of Massachusetts Medical School, Worcester, USA
Tae-Hoon Kim	Zhejiang University of Science and Technology, China
Vladimir Korkhov	Saint Petersburg University, Russia
Takashi Naka	Kyushu Sangyo University, Japan
Rafael D. C. Santos	National Institute for Space Research, Brazil
Maribel Yasmina Santos	University of Minho, Portugal
Anastasia Stratigea	National Technical University of Athens, Greece

Workshop and Session Organizing Chairs

Beniamino Murgante	University of Basilicata, Italy
Chiara Garau	University of Cagliari, Italy

Award Chair

Wenny Rahayu	La Trobe University, Australia

Publicity Committee Chairs

Elmer Dadios	De La Salle University, Philippines
Nataliia Kulabukhova	Saint Petersburg University, Russia
Daisuke Takahashi	Tsukuba University, Japan

Shangwang Wang	Beijing University of Posts and Telecommunications, China

Local Organizing Committee Chairs

Doan Quang Tu	Academy of Military Science and Technology, Hanoi, Vietnam
Ho Sy Tam	Thuyloi University, Vietnam
Le Quang Tuan	Thuyloi University, Vietnam
Nguyen Huu Quynh	Thuyloi University, Vietnam
Ta Quang Chieu	Thuyloi University, Vietnam

Technology Chair

Damiano Perri	University of Perugia, Italy

Program Committee

Vera Afreixo	University of Aveiro, Portugal
Vladimir Alarcon	Northern Gulf Institute, USA
Filipe Alvelos	University of Minho, Portugal
Debora Anelli	Polytechnic University of Bari, Italy
Hartmut Asche	Hasso-Plattner-Institut für Digital Engineering, Germany
Ginevra Balletto	University of Cagliari, Italy
Socrates Basbas	Aristotle University of Thessaloniki, Greece
David Berti	ART SpA, Italy
Michela Bertolotto	University College Dublin, Ireland
Debnath Bhattacharyya	Koneru Lakshmaiah University, India
Sandro Bimonte	CEMAGREF, TSCF, France
Ana Cristina Braga	University of Minho, Portugal
Tiziana Campisi	Kore University of Enna, Italy
Yves Caniou	Lyon University, France
José A. Cardoso e Cunha	Universidade Nova de Lisboa, Portugal
Rui Cardoso	University of Beira Interior, Portugal
Leocadio G. Casado	University of Almeria, Spain
Mete Celik	Erciyes University, Turkey
Maria Cerreta	University of Naples Federico II, Italy
Mauro Coni	University of Cagliari, Italy

Florbela Maria da Cruz Domingues Correia	Polytechnic Institute of Viana do Castelo, Portugal
Roberto De Lotto	University of Pavia, Italy
Marcelo De Paiva Guimaraes	Federal University of Sao Paulo, Brazil
Frank Devai	London South Bank University, UK
Joana Matos Dias	University of Coimbra, Portugal
Laila El Ghandour	Heriot Watt University, UK
Rafida M. Elobaid	Canadian University Dubai, United Arab Emirates
Maria Irene Falcao	University of Minho, Portugal
Florbela P. Fernandes	Polytechnic Institute of Bragança, Portugal
Paula Odete Fernandes	Polytechnic Institute of Bragança, Portugal
Adelaide de Fátima Baptista Valente Freitas	University of Aveiro, Portugal
Valentina Franzoni	University of Perugia, Italy
Andreas Fricke	University of Potsdam, Germany
Raffaele Garrisi	Centro Operativo per la Sicurezza Cibernetica, Italy
Maria Giaoutzi	National Technical University, Athens, Greece
Salvatore Giuffrida	University of Catania, Italy
Teresa Guarda	Universidad Estatal Peninsula de Santa Elena, Ecuador
Sevin Gümgüm	Izmir University of Economics, Turkey
Malgorzata Hanzl	Technical University of Lodz, Poland
Maulana Adhinugraha Kiki	Telkom University, Indonesia
Clement Ho Cheung Leung	Chinese University of Hong Kong, China
Andrea Lombardi	University of Perugia, Italy
Marcos Mandado Alonso	University of Vigo, Spain
Ernesto Marcheggiani	Katholieke Universiteit Leuven, Belgium
Antonino Marvuglia	Luxembourg Institute of Science and Technology, Luxembourg
Michele Mastroianni	University of Salerno, Italy
Hideo Matsufuru	High Energy Accelerator Research Organization, Japan
Alfredo Milani	University of Perugia, Italy
Fernando Miranda	Universidade do Minho, Portugal
Giuseppe Modica	University of Reggio Calabria, Italy
Louiza de Macedo Mourelle	State University of Rio de Janeiro, Brazil
Nadia Nedjah	State University of Rio de Janeiro, Brazil
Paolo Nesi	University of Florence, Italy
Rajdeep Niyogi	Indian Institute of Technology Roorkee, India
Suzan Obaiys	University Malaya, Malaysia
Marcin Paprzycki	Polish Academy of Sciences, Poland

Eric Pardede	La Trobe University, Australia
Ana Isabel Pereira	Polytechnic Institute of Bragança, Portugal
Damiano Perri	University of Perugia, Italy
Massimiliano Petri	University of Pisa, Italy
Telmo Pinto	University of Coimbra, Portugal
Maurizio Pollino	ENEA, Italy
Alenka Poplin	Iowa State University, USA
Marcos Quiles	Federal University of São Paulo, Brazil
Humberto Rocha	University of Coimbra, Portugal
Marzio Rosi	University of Perugia, Italy
Manna Sheela Rani Chetty	Koneru Lakshmaiah University, India
Lucia Saganeiti	University of L'Aquila, Italy
Tamie Salter	Citizen Alerts Inc., Canada
Francesco Scorza	University of Basilicata, Italy
Marco Paulo Seabra dos Reis	University of Coimbra, Portugal
Jie Shen	University of Michigan, USA
Chien Sing Lee	Sunway University, Malaysia
Francesco Tajani	Sapienza University of Rome, Italy
Rodrigo Tapia-McClung	Centro de Investigación en Ciencias de Información Geoespacial, Mexico
Eufemia Tarantino	Polytechnic of Bari, Italy
Sergio Tasso	University of Perugia, Italy
Ana Paula Teixeira	Universidade do Minho, Portugal
Maria Filomena Teodoro	IST ID, Instituto Superior Técnico, Portugal
Yiota Theodora	National Technical University of Athens, Greece
Carmelo Torre	Polytechnic of Bari, Italy
Giuseppe A. Trunfio	University of Sassari, Italy
Toshihiro Uchibayashi	Kyushu University, Japan
Marco Vizzari	University of Perugia, Italy
Frank Westad	Norwegian University of Science and Technology, Norway
Fukuko Yuasa	High Energy Accelerator Research Organization, Japan
Ljiljana Zivkovic	Republic Geodetic Authority, Serbia

Workshops

Advances in Artificial Intelligence Learning Technologies: Blended Learning, STEM, Computational Thinking and Coding (AAILT 2024)

Workshop Organizers

Alfredo Milani	University of Perugia, Italy
Valentina Franzoni	University of Perugia, Italy
Sergio Tasso	University of Perugia, Italy

Workshop Program Committee Members

Li Yuanxi	Hong Kong Baptist University, Hong Kong, China
Valentino Santucci	University for Foreigners, Perugia, Italy
Krassimir Markov	Institute of Information Theories and Applications, Sofia, Bulgaria
Clement Leung	Chinese University of Hong Kong, China
Rajdeep Niyogi	Indian Institute of Technology, Rooorkee, India

Advanced and Innovative Web Apps 2024 (AIWA 2024)

Workshop Organizers

Osvaldo Gervasi	University of Perugia, Italy
Damiano Perri	University of Perugia, Italy

Workshop Program Committee Members

Tamie Salter	Citizen Alert Inc., Canada
Paolo Nesi	University of Florence, Italy
Tae Hoon Kim	Zhejiang University of Science and Technology, China
Debnath Bhattacharyya	Koneru Lakshmaiah Education Foundation, India
David Berti	ART SpA, Italy

Advanced Processes of Mathematics and Computing Models in Complex Computational Systems (ACMC 2024)

Workshop Organizers

Yeliz Karaca	University of Massachusetts Chan Medical School and Massachusetts Institute of Technology, USA
Dumitru Baleanu	Cankaya University, Turkey
Osvaldo Gervasi	University of Perugia, Italy
Yudong Zhang	University of Leicester, UK
Majaz Moonis	University of Massachusetts Medical School, USA

Workshop Program Committee Members

Tamie Salter	Citizen Alert Inc., Canada
TaiHoon Kim	Konkuk University, South Korea
Debnath Bhattacharyya	Koneru Lakshmaiah Education Foundation, India
Massimiliano Nicolini	OliTec Foundation, Italy
Martin Bohner	Missouri University of Science and Technology, Missouri, USA
René Lozi	Université Côte d'Azur, France
Ravi P. Agarwal	Texas A&M University-Kingsville, USA
Aziz Dursun	Virginia Tech, USA
Muhammad Attique Khan	HITEC University, Pakistan and Lebanese American University, Lebanon
Rasulova Mukhayo	National University Uzbekistan, Uzbekistan

Advances in Information Systems and Technologies for Emergency Management, Risk Assessment and Mitigation Based on the Resilience Concepts (ASTER 2024)

Workshop Organizers

Maurizio Pollino	Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Italy
Marco Vona	University of Basilicata, Italy

Alessandro Giocoli	Italian National Agency for New Technologies, Energyand Sustainable Economic Development, Italy
Chiara Ormando	Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Italy
Angelo Anelli	Italian National Research Council, Italy

Workshop Program Committee Members

Gregorio D'Agostino	Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Italy
Christian Bignami	INGV, Italy
Paolo Clemente	Anti-Seismic Systems International Society, ASSISI, USA
Sonia Giovinazzi	Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Italy

Advances in Web-Based Learning 2024 (AWBL 2024)

Workshop Organizers

Mustafa Inceoglu	Ege University, Turkey
Birol Ciloglugil	Ege University, Turkey

Workshop Program Committee Members

Birim Balci	Celal Bayar University, Turkey
Burak Galip Aslan	Izmir Yuksek Teknoloji University, Turkey
Mahmut Unan	University of Alabama, USA
Nisha S. Raj	Global Indian International School, Japan
Oylum Alatlı	Ege University, Turkey

Blockchain and Distributed Ledgers: Technologies and Applications (BDLTA 2024)

Workshop Organizers

Vladimir Korkhov	Saint Petersburg State University, Russia
Elena Stankova	Saint Petersburg State University, Russia
Nataliia Kulabukhova	Saint Petersburg State University, Russia

Workshop Program Committee Members

Vasily Solodkov	Higher School of Economics Banking Institute
Alexander Bogdanov	St. Petersburg State University, Russia
Alexander Degtyarev	St. Petersburg State University, Russia
Dmitry Vasiunin	Deutsche Telekom Cloud Services E.P.E., Greece
Serob Balyan	National Academy of Sciences of Armenia, Armenia
Suren Abrahamyan	Osensus Arm LLC, Armenia
Ashot Gevorkyan	National Academy of Sciences of Armenia, Armenia
Martin Vala	Univerzita Pavla Jozefa Šafárika Košiciach, Košice, Slovakia
Nodir Zaynalov	Tashkent University of Information Technologies, Uzbekistan
Michail Panteleyev	St. Petersburg Electrotecnical University, Russia
Nikolay Peryazev	Irkutsk State University, Irkutsk, Russia

Computational and Applied Mathematics (CAM 2024)

Workshop Organizers

Maria Irene Falcao	University of Minho, Portugal
Fernando Miranda	University of Minho, Portugal

Workshop Program Committee Members

Ricardo Severino	University of Minho, Portugal
Helmuth Malonek	University of Aveiro, Portugal
Isabel Cacao	University of Aveiro, Portugal
Graça Tomaz	Polytechnic of Guarda, Portugal

Rosário Fernandes	University of Minho, Portugal
Lidia Aceto	University of Piedmont Oriental, Italy
Patrícia Beites	University of Beira Interior, Portugal
Regina de Almeida	University of Trás-os-Montes e Alto Douro, Portugal
Luís Ferrás	University of Porto, Portugal
Helmuth Malonek	University of Aveiro, Portugal
João Morais	Autonomous Technological Institute of Mexico, Mexico
Yilmaz Simsek	Akdeniz University, Turkey

Computational and Applied Statistics (CAS 2024)

Workshop Organizer

Ana Cristina Braga	University of Minho, Portugal

Workshop Program Committee Member

Adelaide Freitas	University of Aveiro, Portugal
Ângela Silva	University of Minho, Portugal
Arminda Manuela Gonçalves	University of Minho, Portugal
Arunasalam Rahunanthan	Central State University, USA
Elisete Correia	University of Trás-os-Montes e Alto Douro, Portugal
Frank Westad	Norwegian University of Science and Technology, Norway
Humberto Rocha	University of Coimbra, Portugal
Ivan Rodriguez Conde	University of Arkansas, USA
Lino Costa	University of Minho, Portugal
Marco Reis	University of Coimbra, Portugal
Maria Filipa Mourão	Polytechnic Institute of Viana do Castelo, Portugal
Martín Pérez Pérez	University of Vigo, Spain
Michal Abrahamowicz	McGill University, Canada
Vanda Lourenço	New University of Lisbon, Portugal
Vera Afreixo	University of Aveiro, Portugal

Cyber Intelligence and Applications (CIA 2024)

Workshop Organizer

Gianni D'Angelo	University of Salerno, Italy

Workshop Program Committee Members

Massimo Ficco	University of Salerno, Italy
Marcello Trovati	Edge Hill University, UK
Michal Choras	Bydgoszcz University of Science and Technology, Poland

Computational Methods, Statistics and Industrial Mathematics (CMSIM 2024)

Workshop Organizers

Maria Filomena Teodoro	University of Lisbon and Portuguese Naval Academy, Portugal
Marina A. P. Andrade	University Institute of Lisbon, Portugal
Maria de Fátima Alves de Pina	University Institute of Lisbon, Portugal

Workshop Program Committee Members

Ricardo Moura	University of Lisboa and FCT, Portugal
Aldina Correia	Escola Superior de Tecnologia e Gestão, Portugal
Eliana Costa	Escola Superior de Tecnologia e Gestão, Portugal
Ana Borges	Escola Superior de Tecnologia e Gestão, Portugal
Cristina Lopes	ISCAP, Portugal
Fernando Carapau	University of Evora, Portugal
Fernanda Costa	University of Minho, Portugal
Maria Luísa Morgado	University of Trás os Montes e Alto Douro and University of Lisboa, Portugal
Ana Isabel Pereira	Instituto Politécnico de Bragança, Portugal
Bruna Ramos	University of Minho, Portugal
Rosário Ramos	Universidade Aberta, Portugal
Elisabete Carolino	Escola Superior da Saúde de Lisboa, Portugal
Sofia Rézio	Instituto Politécnico de Lisboa, Portugal
Matteo Sacchet	University of Turin, Italy

Marina Marchisio Conte	University of Turin, Italy
António Seijas-Macias	University of Coruña, Spain
Luís F. A. Teodoro	University of Glasgow, UK and University of Oslo, Norway
Christos Kitsos	University of West Attica, Greece

Computational Optimization and Applications (COA 2024)

Workshop Organizers

Ana Maria A. C. Rocha	University of Minho, Portugal
Humberto Rocha	University of Coimbra, Portugal

Workshop Program Committee Members

Eligius M. T. Hendrix	University of Málaga, Spain
Joana Matos Dias	University of Coimbra, Portugal
Ana Isabel Pereira	Polytechnic Institute of Bragança, Portugal
Filipe Alvelos	Univeristy of Minho, Portugal
Emerson José de Paiva	Federal University of Itajubá, Brazil

Computational Astrochemistry (CompAstro 2024)

Workshop Organizers

Marzio Rosi	University of Perugia, Italy
Nadia Balucani	University of Perugia, Italy
Daniela Ascenzi	University of Trento, Italy
Stefano Falcinelli	University of Perugia, Italy

Workshop Program Committee Members

Albert Rimola	Universitat Autònoma de Barcelona, Spain
Dimitrios Skouteris	Master-Tec, Perugia, Italy
Piero Ugliengo	University of Turin, Italy
Andrea Lombardi	University of Perugia, Italy
Piergiorgio Casavecchia	University of Perugia, Italy
Fernando Pirani	University of Perugia, Italy
Costanza Borghesi	University of Perugia, Italy

Gabriella Digenova	University of Perugia, Italy
Lisa Giani	Grenoble Alpes University, France
Marco Parriani	University of Perugia, Italy
Cecilia Coletti	University of Chieti, Italy
Massimiliano Aschi	University of L'Aquila, Italy
Emilia Dearagao	University of Perugia, Italy
Giacomo Pannacci	University of Perugia, Italy
Gianmarco Vanuzzo	University of Perugia, Italy

Computational Methods for Porous Geomaterials (CompPor 2024)

Workshop Organizers

Vadim Lisitsa	Russian Academy of Science, Russia
Evgeniy Romenski	Russian Academy of Science, Russia

Workshop Program Committee Members

Kirill Gadylshin	Russian Academy of Science, Russia
Tayana Khachkova	Russian Academy of Science, Russia
Dmitri Prokhorov	Russian Academy of Science, Russia
Mikahil Novikov	Russian Academy of Science, Russia

Workshop on Computational Science and HPC (CSHPC 2024)

Workshop Organizers

Elise De Doncker	Western Michigan University, USA
Fukuko Yuasa	High Energy Accelerator Research Organization, Japan
Hideo Matsufuru	High Energy Accelerator Research Organization, Japan

Workshop Program Committee Members

Tadashi Ishikawa	High Energy Accelerator Research Organization, Japan
Hiroshi Daisaka	Hitotsubashi University, Japan
Naohito Nakasato	University Aizu, Japan

Takahiro Ueda	Juntendo University, Japan
Khiem Hong Phan	Duy Tan University, Vietnam
Naohito Nakasato	University Aizu, Japan
Tasnim Gharaibeh	Kalamazoo College, USA
Robert Makin	Western Michigan University, USA

Cities, Technologies and Planning (CTP 2024)

Workshop Organizers

Beniamino Murgante	University of Basilicata, Italy
Giuseppe Borruso	University of Trieste, Italy
Malgorzata Hanzl	Lodz University of Technology, Poland
Anastasia Stratigea	National Technical University of Athens, Greece
Ljiljana Zivkovic	Republic Geodetic Authority, Serbia
Ginevra Balletto	University of Cagliari, Italy

Workshop Program Committee Members

Silvia Battino	University of Sassari, Italy
Mara Ladu	University of Cagliari, Italy
Maria del Mar Munoz Leonisio	University of Cadiz, Spain
Ahinoa Amaro Garcia	Univeristy of Las Palmas of Gran Canaria, Spain
Maria Attard	University of Malta, Malta
Enrico Dagostini	University of Malta, Malta
Francesca Krasna	University of Trieste, Italy
Brisol García García	Polytechnic University of Quintana Roo, Mexico
Tu Anh Trinh	College of Technology and Design for UEH University, Vietnam
Giovanni Mauro	University of Campania Luigi Vanvitelli, Italy
Maria Ronza	University of Naples, Federico II, Italy
Massimiliano Bencardino	University of Salerno, Italy

Sustainable Digital Circular Economy (DiCE 2024)

Workshop Organizers

Ginevra Balletto	University of Cagliari, Italy
Stefano Epifani	Digital Sustainability Foundation, Italy

Stefano Carboni	University of Sassari, Italy
Francesca Sinatra	University of Cagliari, Italy
Salvatore Dore	University of Sassari, Italy
Andrea Gallo	University of Trieste, Italy

Workshop Program Committee Members

Giuseppe Borruso	University of Trieste, Italy
Silvia Battino	University of Sassari, Italy
Beniamino Murgante	University of Basilicata, Italy
Mara Ladu	University of Cagliari, Italy
Luigi Mundula	University of Perugia, Italy
Maria Attard	University of Malta, Malta
Enrico Dagostini	University of Malta, Malta
Emilio Ghiani	University of Cagliari, Italy
Marco Naseddu	University of Cagliari, Italy
Balázs Kulcsaár	University of Debrecen, Hungary
Tu Anh Trinh	College of Technology and Design for UEH University, Vietnam
Giovanni Mauro	University of Campania Luigi Vanvitelli, Italy
Maria Ronza	University of Naples, Federico II, Italy
Massimiliano Bencardino	University of Salerno, Italy

Evaluating Inner Areas Potentials (EIAP 2024)

Workshop Organizers

Diana Rolando	Polytechnic of Turin, Italy
Alice Barreca	Polytechnic of Turin, Italy
Manuela Rebaudengo	Polytechnic of Turin, Italy
Giorgia Malavasi	Polytechnic of Turin, Italy

Workshop Program Committee Members

John Accordino	Virginia Commonwealth University, USA
Sara Favargiotti	University of Trento, Italy
Maddalena Ferretti	Polytechnic University of Marche, Italy
Daniel Laven	Mid Sweden University, Sweden
Barbara Lino	University of Palermo, Italy
Umberto Mecca	Polytechnic University of Turin, Italy

Lorenzo Savio	Polytechnic University of Turin, Italy
Asja Aulisio	Polytechnic University of Turin, Italy

Econometrics and Multidimensional Evaluation of Urban Environment (EMEUE 2024)

Workshop Organizers

Carmelo Maria Torre	Polytechnic of Bari, Italy
Francesco Tajani	Sapienza University of Rome, Italy
Pierluigi Morano	Polytechnic of Bari, Italy
Simona Panaro	University of Sussex, UK
Maria Cerreta	University of Naples Federico II, Italy
Debora Anelli	Polytechnic of Bari, Italy

Workshop Program Committee Members

Pierfrancesco de Paola	University of Naples Federico II, Italy
Daniela Tavano	University of Calabria, Italy
Giuseppe Cerullo	Sapienza University of Rome, Italy
Francesco Paolo del Giudice	Sapienza University of Rome, Italy
Marco Locurcio	Polytechnic University of Bari, Italy
Maria Rosa Trovato	University of Catania, Italy
Felicia di Liddo	Polytechnic University of Bari, Italy
Maria Paz Saez Perez	University of Granada, Spain
Yasmine Selim	Ain Shams University, Cairo
Hasan Mara	Indian Institute of Technology Roorkee, India
Philipp Wiesner	Technical University of Berlin, Germany
Maria Gamboa Perez	Complutense University of Madrid, Spain
Manuel Yanez	Universidad Autónoma de Madrid, Spain
Lucia Ika Fitriastuti	Solusi Bisnis Indonesia, Indonesia
Frank Devai	London South Bank University, UK
Frank Westad	Norwegian University of Science and Technology, Norway
Eugenio Muccio	University of Naples Federico II, Italy
Chiara Mazzarella	TU Delft, The Netherlands
Daniele Cannatella	TU Delft, The Netherlands
Sabrina Sacco	University of Naples Federico II, Italy
Piero Zizzania	University of Naples Federico II, Italy
Stefano Cuntò	University of Naples Federico II, Italy

Sveva Ventre	University of Naples Federico II, Italy
Caterina Loffredo	University of Naples Federico II, Italy
Giuseppe Ciciriello	University of Naples Federico II, Italy
Maria Somma	University of Naples Federico II, Italy
Ludovica La Rocca	University of Naples Federico II, Italy
Gaia Daldanise	National Research Council, Italy
Giuliano Poli	University of Naples Federico II, Italy

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

Workshop Organizers

Ginevra Balletto	University of Cagliari, Italy
Emilio Ghiani	University of Cagliari, Italy
Roberto De Lotto	University of Pavia, Italy
Alessandra Marra	University of Salerno, Italy
Riccardo Trevisan	University of Cagliari, Italy
Balázs Kulcsár	University of Debrecen, Hungary

Workshop Program Committee Members

Jacopo Torriti	University of Reading, UK
Roberto Gerundo	University of Salerno, Italy
Luigi Mundula	University of Perugia, Italy
Mara Ladu	University of Cagliari, Italy
Giuseppe Borruso	University of Trieste, Italy
Tu Anh Trinh	College of Technology and Design for UEH University, Vietnam
Giovanni Mauro	University of Campania Luigi Vanvitelli, Italy
Maria Ronza	University of Naples, Federico II, Italy
Massimiliano Bencardino	University of Salerno, Italy

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

Workshop Organizers

Sabrina Lai	University of Cagliari, Italy
Corrado Zoppi	University of Cagliari, Italy
Francesco Scorza	University of Basilicata, Italy

Beniamino Murgante	University of Basilicata, Italy
Floriana Zucaro	University of Naples Federico II, Italy
Carmela Gargiulo	University of Naples Federico II, Italy

Workshop Program Committee Members

Carmen Guida	University of Naples Federico II, Italy
Irina Di Ruocco	Insubria University, Italy
Silvia Rossetti	University of Parma, Italy
Barbara Caselli	University of Parma, Italy
Gloria Pellicelli	University of Parma, Italy
Federica Leone	University of Cagliari, Italy
Federica Isola	University of Cagliari, Italy
Francesca Leccis	University of Cagliari, Italy
Francesca Perrone	Sapienza University of Rome, Italy
Angela Pilogallo	Italian National Research Council, Italy
Alfonso Annunziata	University of Basilicata, Italy
Alessandro Marucci	University of L'Aquila, Italy
Francesco Zullo	University of L'Aquila, Italy
Gizem Dinç	Süleyman Demirel University, Turkey
Atila Gul	Süleyman Demirel University, Turkey
Sarah Scheiber	University of Malta, Malta
Matteo Caglioni	Université Côte d'Azur, France

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

Workshop Organizers

Valentina Franzoni	University of Perugia, Italy
Alfredo Milani	University of Perugia, Italy
Jordi Vallverdu	University Autonoma Barcelona, Spain

Workshop Program Committee Members

Sergio Tasso	University of Perugia, Italy
Yuanxi Li	Hong Kong Baptist University, Hong Kong, China
Daniele Mezzetti	Santa Maria della Misericordia Hospital of Perugia, Italy
Abeer Dyoub	L'Aquila University, Italy

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

Workshop Organizers

Bernady Apduhan	Kyushu Sangyo University, Japan
Rafael Santos	National Institute for Space Research, Brazil

Workshop Program Committee Members

Agustinus Borgy Waluyo	Monash University, Australia
Andre Ricardo Abed Grégio	Federal University of Parana, Brazil
Earl Ryan Aleluya	MSU-Iligan Institute of Technology, Philippines
Kai Cheng	Kyushu Sangyo University, Japan
Alvaro Fazenda	Federal University of São Paulo, Brazil
Yusuke Gotoh	Okayama University, Japan
Eric Pardede	La Trobe University, Australia
Yasuaki Sumida	Kyushu Sangyo University, Japan
Kazuaki Tanaka	Kyushu Institute of Technology, Japan
Toshihiro Uchibayashi	Kyushu University, Japan
Toshihiro Yamauchi	Okayama University, Japan
Fenghui Yao	Tennessee State University, USA

Geographical Analysis, Urban Modeling, Spatial Statistics (Geog-An-Mod 2024)

Workshop Organizers

Beniamino Murgante	University of Basilicata, Italy
Giuseppe Borruso	University of Trieste, Italy
Harmut Asche	Hasso-Plattner-Institut für Digital Engineering, Germany
Andreas Fricke	Hasso-Plattner-Institut für Digital Engineering, Germany
Rodrigo Tapia McClung	Centro de Investigación en Ciencias de Información Geoespacial, Mexico

Workshop Program Committee Members

Ginevra Balletto	University of Cagliari, Italy
Silvia Battino	University of Sassari, Italy
Mara Ladu	University of Cagliari, Italy
Marco Mazzarino	IUAV Univeristy Venice, Italy
Maria del Mar Munoz Leonisio	Univeristy of Cadiz, Spain
Ahinoa Amaro Garcia	University of Las Palmas of Gran Canaria, Spain
Veronica Camerada	University of Sassari, Italy
Maria Attard	University of Malta, Malta
Enrico Dagostini	University of Malta, Malta
Francesca Krasna	University of Trieste, Italy
Malgorzata Hanzl	Lodz University of Technology, Poland
Anastasia Stratigea	National Technical University of Athens, Greece
Tu Anh Trinh	College of Technology and Design for UEH University, Vietnam
Giovanni Mauro	University of Campania Luigi Vanvitelli, Italy
Maria Ronza	University of Naples, Federico II, Italy
Massimiliano Bencardino	University of Salerno, Italy

Geomatics for Resource Monitoring and Management (GRMM 2024)

Workshop Organizers

Alessandra Capolupo	Polytechnic of Bari, Italy
Eufemia Tarantino	Polytechnic of Bari, Italy
Alberico Sonnessa	Polytechnic of Bari, Italy

Workshop Program Committee Members

Umberto Fratino	Polytechnic of Bari, Italy
Valeria Monno	Polytechnic of Bari, Italy
Antonino Maltese	University of Palermo, Italy
Athos Agapiou	Cyprus University of Technology, Cyprus
Michele Mangiameli	University of Catania, Italy
Angela Gorgoglione	University of la República de Uruguay, Uruguay
Roberta Ravanelli	Sapienza University of Rome, Italy
Alessandra Mascitelli	D'Annunzio University of Chieti–Pescara, Italy
Ester Scotto di Perta	University of Naples, Federico II, Italy

Giacomo Caporusso	National Research Council, Italy
Andrea Montanino	University of Naples, Federico II, Italy
Antonino Iannuzzo	University of Sannio, Benevento, Italy
Silvano Dal Sasso	University of Basilicata, Potenza, Italy
Laura Mirra	National Research Council, Water Research Institute, Italy
Alessandro Pagano	National Research Council, Water Research Institute, Italy
Francesco Chiaravalloti	National Research Council, Water Research Institute, Italy
Francesco Di Capua	University of Basilicata, Italy
Stefania Santoro	National Research Council, Water Research Institute, Italy
Cinzia Albertini	National Research Council, IREA, Italy
Alessandra Saponieri	University of Salento, Italy

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

Workshop Organizers

Teresa Guarda	Peninsula State University of Santa Elena, Ecuador
José María Díaz Nafría	Madrid Open University, Spain
Filipe Portela	University of Minho, Portugal

Workshop Program Committee Members

Arnulfo Alanis	Instituto Tecnologico de Tijuana, Mexico
Bruno Sousa	University of Coimbra, Portugal
Carlos Balsa	Instituto Politécnico de Bragança, Portugal
Filipe Mota Pinto	Instituto Politécnico de Leiria, Portugal
Gustavo Gatica	Universidad Andrés Bello, Chile
Isabel Lopes	Instituto Politécnico de Bragança, Portugal
José María Díaz Nafría	Universidad a Distancia, Spain
Maria Fernanda Augusto	BiTrum Research Group, Spain
Maria Isabel Ribeiro	Instituto Politécnico Bragança, Portugal
Modestos Stavrakis	University of the Aegean, Greece
Simone Belli	Universidad Complutense de MadridSpain
Walter Lopes Neto	Instituto Federal de Educação, Brazil

Regenerating Brownfields Enhancing Urban Resilience Appeal (INFERENCE 2024)

Workshop Organizers

Francesca Moraci	Mediterranea University of Reggio Calabria, Italy
Maurizio Oddo	University of Enna Kore, Italy
Antonella Versaci	University of Enna Kore, Italy
Celestina Fazia	University of Enna Kore, Italy
Tiziana Campisi	University of Enna Kore, Italy
Kh Md Nahiduzzaman	University of British Columbia, Canada

Workshop Program Committee Members

Alessandro Baracco	University of Enna Kore, Italy
Kaoutare Amini Alaoui	Mohammed VI Polytechnic University, UM6P, Morocco
Maurizio Errigo	Sapienza University of Rome, Italy
Marsia Marino	Sapienza University of Rome, Italy
Nessrine Moumen	Mohammed VI Polytechnic University, UM6P, Morocco
Francesca Perrone	Sapienza University of Rome, Italy
Pasquale Pizzimenti	Mediterranea University of Reggio Calabria, Italy
Barbara Scala	University of Brescia, Italy
Clarastella Vicari Aversa	Mediterranea University of Reggio Calabria, Italy

International Workshop on Territorial Planning to Integrate Risk and Urban Ontologies (IWPRO 2024)

Workshop Organizers

Elisabetta Maria Venco	University of Pavia, Italy
Beniamino Murgante	University of Basilicata, Italy
Roberto De Lotto	University of Pavia, Italy
Caterina Pietra	University of Pavia, Italy

Workshop Program Committee Members

Stefano Borgo	National Research Council, Italy
Valentina Costa	University of Genoa, Italy
Pajouh Danesh	Middle East Technical University, Turkey

Ilaria Delponte	University of Genoa, Italy
Lorena Fiorini	University of L'Aquila, Italy
Veronica Gazzola	Polytechnic of Milan, Italy
Ghazaleh Goodarzi	Islamic Azad University, Iran
Michele Grimaldi	University of Salerno, Italy
Alessandra Marra	University of Salerno, Italy
Naghmeh Mohammadpourlima	Akademi University, Finland
Francesca Pirlone	University of Genoa, Italy
Silvia Rossetti	University of Parma, Italy
Lucia Saganeiti	University of L'Aquila, Italy
Bahareh Shahsavari	University of Minnesota, USA
Ilenia Spadaro	University of Genoa, Italy
Maria Rosaria Stufano Melone	Polytechnic of Bari, Italy

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

Workshop Organizers

Gianfranco Fancello	University of Cagliari, Italy
Francesco Piras	University of Cagliari, Italy
Tanja Congiu	University of Sassari, Italy
Mara Ladu	University of Cagliari, Italy
Martina Sinatra	University of Cagliari, Italy
Ginevra Balletto	University of Cagliari, Italy

Workshop Program Committee Members

Italo Meloni	University of Cagliari, Italy
Tu Anh Trinh	College of Technology and Design for UEH University, Vietnam
Giuseppe Borruso	University of Trieste, Italy
Luigi Mundula	University of Perugia, Italy
Francesca Sinatra	University of Trieste, Italy
Salvatore Dore	University of Trieste, Italy
Andrea Gallo	University of Trieste, Italy
Marcello Tadini	University of Eastern Piedmont, Italy
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
Maria Attard	University of Malta, Malta
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)

Workshop Organizers

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
Jesús González-Feliu	Excelia Business School, La Rochelle, France

Workshop Program Committee Members

Paola Panuccio	Mediterranea University of Reggio Calabria, Italy
Domenica Savia Pellicano	Mediterranean University of Reggio Calabria, Italy
Alexandros Nikitas	University of Huddersfield, UK
Antonio Polimeni	University of Messina, Italy
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)

Workshop Organizers

Maria Cerreta	University of Naples Federico II, Italy
Giuliano Poli	University of Naples Federico II, Italy
Daniele Cannatella	TU Delft, The Netherlands

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

Workshop Program Committee Members

Maria Lucia Raiola	University of Naples Federico II, Italy
Eugenio Muccio	University of Naples Federico II, Italy
Chiara Mazzarella	TU Delft, The Netherlands
Sabrina Sacco	University of Naples Federico II, Italy
Piero Zizzania	University of Naples Federico II, Italy
Stefano Cuntò	University of Naples Federico II, Italy
Sveva Ventre	University of Naples Federico II, Italy
Caterina Loffredo	University of Naples Federico II, Italy
Giuseppe Ciciriello	University of Naples Federico II, Italy
Laura Di Tommaso	University of Naples Federico II, Italy
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)

Workshop Organizers

Vanessa Assumma	University of Bologna, Italy
Caterina Caprioli	Politechnic of Turin, Italy
Giulia Datola	Politechnic of Turin, Italy
Federico Dell'Anna	Politechnic of Turin, Italy
Marta Dell'Ovo	Politechnic of Milan, Italy
Marco Rossitti	Politechnic of Milan, Italy

Workshop Program Committee Members

Maksims Feofilovs	Riga Technical University, Latvia
Ossama Abdelwahab	University of Bari, Italy
Mariarosaria Angrisano	Pegaso Telematic University, Italy
Francesca Torrieri	Polytechnic of Milan, Italy
Maurizio Pioletti	University of Padua, Italy
Daniela Tavano	University of Calabria, Italy
Simone Persico	Polytechnic of Turin, Italy

Chiara D'Alpaos	University of Padua, Italy
Ezgi Şahin	Mersin University, Turkey
Giorgia Sugoni	LINKS Foundation, Italy
Rubina Canesi	University of Padua, Italy
Giulia Marzani	University of Bologna, Italy
Danny Casprini	Polytechnic of Milan, Italy
Simona Barbaro	University of Palermo, Italy
Giulio Cavana	Polytechnic of Turin, Italy
Diana Rolando	Polytechnic of Turin, Italy
Giuliano Poli	University of Naples Federico II, Italy
Francesco Sica	University of Rome La Sapienza, Italy
Sabrina Lai	University of Cagliari, Italy

Models and Indicators for Assessing and Measuring the Urban Settlement Development in the View of Zero Net Land Take by 2050 (MOVEto0 2024)

Workshop Organizers

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

Workshop Program Committee Members

Ginevra Balletto	University of Cagliari, Italy
Giuseppe Borruso	University of Trieste, Italy
Chiara Garau	University of Cagliari, Italy
Beniamino Murgante	University of Basilicata, Italy
Ljiljana Zivkovic	MBA, Republic Geodetic Authority, Serbia
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)

Workshop Organizers

Michele Mastroianni	University of Salerno, Italy
Mauro Iacono	University of Campania Luigi Vanvitelli, Italy
Lelio Campanile	University of Campania Luigi Vanvitelli, Italy

Workshop Program Committee Members

Maria Ganzha	Warsaw University of Technology, Poland
Armando Tacchella	University of Genoa, Italy
Alessio Merlo	School for Advanced Defense Studies, Italy
Antonio Iannuzzi	Roma Tre University, Italy
Arcangelo Castiglione	University of Salerno, Italy
Daniel Grzonka	Cracow University of Technology, Poland
Davide Cerotti	University of Piedmont Oriental, Italy

Scientific Computing Infrastructure (SCI 2024)

Workshop Organizers

Vladimir Korkhov	St. Petersburg University, Russia
Elena Stankova	St. Petersburg State University, Russia

Workshop Program Committee Members

Adam Belloum	University of Amsterdam, the Netherlands
Dmitry Vasiunin	Deutsche Telekom Cloud Services E.P.E., Greece
Serob Balyan	National Academy of Sciences of Armenia, Armenia
Suren Abrahamyan	Osensus Arm LLC, Armenia
Ashot Gevorkyan	National Academy of Sciences of Armenia, Armenia
Michal Hnatic	Univerzita Pavla Jozefa Šafárika v Košiciach, Slovakia
Martin Vala	Univerzita Pavla Jozefa Šafárika v Košiciach, Slovakia
Nodir Zaynalov	Tashkent University of Information Technologies, Uzbekistan
Michail Panteleyev	St. Petersburg Electrotecnical University, Russia

Nikolay Peryazev	Irkutsk State University, Irkutsk, Russia
Alexander Degtyarev	St. Petersburg State University, Russia
Alexander Bogdanov	St. Petersburg State University, Russia
Nataliia Kulabukhova	SberAutoTech, Russia

Downscale Agenda 2030 (SDGscale 2024)

Workshop Organizers

Anna Richiedei	University of Brescia, Italy
Michele Pezzagno	University of Brescia, Italy
Ginevra Balletto	University of Cagliari, Italy
Francesca Sinatra	University of Trieste, Italy
Federico Martellozzo	University of Florence, Italy
Tú Anh Trinh	University of Economics Ho Chi Minh City, Vietnam

Workshop Program Committee Members

Giuseppe Borruso	University of Trieste, Italy
Elisabetta Maria Venco	University of Pavia, Italy
Riccardo Privitera	University of Catania, Italy
Elisa Conticelli	University of Bologna, Italy
Giovanni Marinelli	Polytechnic University of Marche, Italy
Francesca Sinatra	University of Trieste, Italy
Salvatore Dore	University of Trieste, Italy
Maria Attard	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

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

Workshop Organizers

Debora Anelli	Polytechnic of Bari, Italy
Pierluigi Morano	Polytechnic of Bari, Italy
Benedetto Manganelli	University of Basilicata, Italy
Francesco Paolo Del Giudice	Sapienza University of Rome, Italy

Workshop Program Committee Members

Laura Gabrielli	University of Ferrara, Italy
Sergio Copiello	University of Venice, Italy
Antonio Nesticò	University of Salerno, Italy
Pierfrancesco De Paola	University of Napoli, Italy
Elena Fregonara	Polytechnic of Turin, Italy
Paola Amoruso	LUM, Italy

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

Workshop Organizers

Giuseppe Borruso	University of Trieste, Italy
Gianfranco Fancello	University of Cagliari, Italy
Patrizia Serra	University of Cagliari, Italy
Silvia Battino	University of Sassari, Italy
Marco Petrelli	Roma Tre University, Italy

Workshop Program Committee Members

Ginevra Balletto	University of Cagliari, Italy
Beniamino Murgante	University of Basilicata, Italy
Marco Mazzarino	IUAV University Venice, Italy
Maria del Mar Munoz Leonisio	University of Cadiz, Spain
Ahinoa Amaro Garcia	University of Las Palmas of Gran Canaria, Spain
Veronica Camerada	University of Sassari, Italy
Brunella Brundu	University of Sassari, Italy
Maria Attard	University of Malta, Malta
Enrico Dagostini	University of Malta, Malta
Tu Anh Trinh	College of Technology and Design for UEH University, Vietnam
Giovanni Mauro	University of Campania Luigi Vanvitelli, Italy
Maria Ronza	University of Naples, Federico II, Italy
Massimiliano Bencardino	University of Salerno, Italy

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

Workshop Organizers

Giuseppe Borruso	University of Trieste, Italy
Marcello Tadini	University of Eastern Piedmont, Italy
Maria del Mar Munoz Leonisio	University of Cádiz, Spain
Maria Attard	University of Malta, Malta
Veronica Camerada	University of Sassari, Italy
Brunella Brundu	University of Sassari, Italy

Workshop Program Committee Members

Ginevra Balletto	University of Cagliari, Italy
Silvia Battino	University of Sassari, Italy
Gianfranco Fancello	University of Cagliari, Italy
Mara Ladu	University of Cagliari, Italy
Martina Sinatra	University of Cagliari, Italy
Francesca Sinatra	University of Trieste, Italy
Salvatore Dore	University of Trieste, Italy
Andrea Gallo	University of Trieste, Italy
Marco Mazzarino	IUAV University Venice, Italy
Enrico Dagostini	University of Malta, Malta
Marco Naseddu	University of Cagliari, Italy
José Ángel Hernández Luis	University of Las Palmas de Gran Canaria, Spain
Maurizio Cociancich	Adriafer, Italy
Giovanni Longo	University of Trieste, Italy
Luca Toneatti	University of Trieste, Italy
Giovanni Mauro	University of Campania Luigi Vanvitelli, Italy
Maria Ronza	University of Naples, Federico II, Italy
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

Ginevra Balletto	University of Cagliari, Italy
Brisol García García	Polytechnic University of Quintana Roo, Mexico
Ainhoa Amaro Garcia	University of Las Palmas of Gran Canarias, Spain

Workshop Program Committee Members

Giuseppe Borruso	University of Trieste, Italy
Beniamino Murgante	University of Basilicata, Italy
Gianfranco Fancello	University of Cagliari, Italy
Mara Ladu	University of Cagliari, Italy
Martina Sinatra	University of Cagliari, Italy
Salvatore Dore	University of Trieste, Italy
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
Giovanni Mauro	University of Campania Luigi Vanvitelli, Italy
Maria Ronza	University of Naples, Federico II, Italy
Massimiliano Bencardino	University of Salerno, Italy

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

Workshop Organizers

Tiziana Campisi	University of Enna Kore, Italy
Socrates Basbas	Aristotle University of Thessaloniki, Greece
Massimo Di Gangi	University of Messina, Italy
Antonio Comi	University of Rome Tor Vergata, Italy
Francesco Russo	Mediterranea University of Reggio Calabria, Italy
Giovanni Tesoriere	University of Enna Kore, Italy

Workshop Program Committee Members

Antonio Polimeni	University of Messina, Italy
Orlando Belcore	University of Messina, Italy
Filippo G. Praticò	Mediterranea University of Reggio Calabria, Italy
Borja Alonso	University of Cantabria, Spain
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

Francesco Scorza	University of Basilicata, Italy
Sabrina Lai	University of Cagliari, Italy
Jolanta Dvarioniene	Kaunas University of Technology, Lithuania

Workshop Program Committee Members

Carmela Gargiulo	University of Naples Federico II, Italy
Floriana Zucaro	University of Naples Federico II, Italy
Corrado Zoppi	University of Cagliari, Italy
Federica Leone	University of Cagliari, Italy
Federica Isola	University of Cagliari, Italy
Francesca Leccis	University of Cagliari, Italy
Francesca Perrone	Sapienza University of Rome, Italy
Angela Pilogallo	Italian National Research Council, Italy
Alfonso Annunziata	University of Basilicata, Italy
Luigi Santopietro	Italian National Research Council, Italy
Beniamino Murgante	University of Basilicata, Italy
Alessandro Marucci	University of L'Aquila, Italy
Francesco Zullo	University of L'Aquila, Italy
Monica Salvia	Italian National Research Council, Italy
Fulvia Pietrapertosa	Italian National Research Council, Italy
Valentin Grecu	Lucian Blaga University, Romania
Georgia Pozoukidou	Aristotle University of Thessaloniki, Greece
Giampiero Lombardini	University of Genoa, Italy

Specifics of Smart Cities Development in Europe (SPEED 2024)

Workshop Organizers

Chiara Garau	University of Cagliari, Italy
Katarína Vitálišová	Matej Bel University, Slovakia
Paolo Nesi	University of Florence, Italy
Anna Vaňová	Matej Bel University, Slovakia
Kamila Borsekova	Matej Bel University, Slovakia
Paola Zamperlin	University of Florence, Italy

Workshop Program Committee Members

Tiziana Campisi	University of Enna Kore, Italy
Giovanna Concu	University of Cagliari, Italy
Claudia Loggia	University of KwaZulu-Natal, South Africa
Alessandro Plaisant	University of Sassari, Italy
Francesca Maltinti	University of Cagliari, Italy
Silvia Rossetti	University of Parma, Italy
Gerardo Carpentieri	University of Naples Federico II, Italy
Carmen Guida	University of Naples Federico II, Italy
Anastasia Stratigea	National Technical University of Athens, Greece
Yiota Theodora	National Technical University of Athens, Greece
Marco Fanfani	University of Florence, Italy
Emanuele Bellini	University of Rome 3, Italy

Smart, Safe and Health Cities (SSHC 2024)

Workshop Organizers

Chiara Garau	University of Cagliari, Italy
Gerardo Carpentieri	University of Naples Federico II, Italy
Carmen Guida	University of Naples Federico II, Italy
Floriana Zucaro	University of Naples Federico II, Italy
Tanja Congiu	University of Sassari, Italy
Martina Carra	University of Brescia, Italy
Benedetto Barabino	University of Brescia, Italy

Workshop Program Committee Members

Rosaria Battarra	Italian National Research Council, Italy
Barbara Caselli	University of Parma, Italy
Francesca Maltinti	University of Cagliari, Italy
Romano Fistola	University of Naples Federico II, Italy
Sabrina Lai	University of Cagliari, Italy
Claudia Loggia	University of KwaZulu-Natal, South Africa
Alessandro Plaisant	University of Sassari, Italy
Silvia Rossetti	University of Parma, Italy
Michela Tiboni	University of Brescia, Italy
John Zacharias	Peking University, China
Thomas Buhler	University of Franche-Comté, France

Aynaz Lotfata	University of California, USA
Lucia Saganeiti	University of L'Aquila, Italy
Francesco Zullo	University of L'Aquila, Italy
Paola Zamperlin	University of Florence, Italy
Katarína Vitálišová	Matej Bel University, Faculty of Economics, Slovakia
Tiziana Campisi	University of Enna Kore, Italy
Caterina Pietra	University of Pavia, Italy
Elisabetta Maria Venco	University of Pavia, Italy
Vincenza Torrisi	University of Catania, Italy

Smart and Sustainable Island Communities (SSIC 2024)

Workshop Organizers

Chiara Garau	University of Cagliari, Italy
Anastasia Stratigea	National Technical University of Athens, Greece
Yiota Theodora	National Technical University of Athens, Greece
Giovanna Concu	University of Cagliari, Italy

Workshop Program Committee Members

Milena Metalkova-Markova	University of Portsmouth, UK
Tarek Teba	University of Portsmouth, UK
Despina Dimelli	Technical University of Crete, Greece
Gerardo Carpentieri	University of Naples Federico II, Italy
Carmen Guida	University of Naples Federico II, Italy
Floriana Zucaro	University of Naples Federico II, Italy
Anestis Gourgiotis	University of Thessaly, Greece
George Tsilimigkas	University of the Aegean, Greece
Maria Panagiotopoulou	National Technical University of Athens, Greece
George Somarakis	National Technical University of Athens, Greece
Harry Kyriakidis	National Technical University of Athens, Greece
Apostolos Lagarias	Univ. of Thessaly, Greece
Paola Zamperlin	University of Florence, Italy
Giuseppina Vacca	University of Cagliari, Italy
Roberto Minunno	Curtin University, Perth, Australia
Claudia Loggia	University of KwaZulu-Natal, South Africa
Francesca Maltinti	University of Cagliari, Italy
Elisabetta Maria Venco	University of Pavia, Italy

From Street Experiments to Planned Solutions (STEPS 2024)

Workshop Organizers

Silvia Rossetti	University of Parma, Italy
Angela Ricciardello	University of Enna Kore, Italy
Francesco Pinna	University of Cagliari, Italy
Chiara Garau	University of Cagliari, Italy
Tiziana Campisi	University of Enna Kore, Italy
Vincenza Torrisi	University of Catania, Italy

Workshop Program Committee Members

Martina Carra	University of Brescia, Italy
Barbara Caselli	University of Parma, Italy
Tanja Congiu	University of Sassari, Italy
Gabriele D'Orso	University of Palermo, Italy
Matteo Ignaccolo	University of Catania, Italy
Md Kh Nahiduzzaman	University of British Columbia, Canada
Muhammad Ahmad Al-Rashid	University of Malaya, Malesia
Alessandro Plaisant	University of Sassari, Italy
Marianna Ruggieri	University of Enna Kore, Italy
Michele Zazzi	University of Parma, Italy

Sustainable Development of Ports (SUSTAINABLEPORTS 2024)

Workshop Organizers

Giuseppe Musolino	Mediterranea University of Reggio Calabria, Italy
Tiziana Campisi	University of Enna Kore, Italy
Efstathios Bouhouras	Aristotle University of Thessaloniki, Greece
Elena Cocuzza	University of Catania, Italy
Gianfranco Fancello	University of Cagliari, Italy
Massimo Di Gangi	University of Messina, Italy

Workshop Program Committee Members

Georgios Vaggelas	National and Kapodistrian University of Athens, Greece
Antonio Polimeni	University of Messina, Italy

Orlando Belcore	University of Messina, Italy
Lucia Dalla Spina	Mediterranea University of Reggio Calabria, Italy
Elen Twerdy	University of Lubljana, Slovenia
Claudia Caballini	Polytechnic University of Turin, Italy

Theoretical and Computational Chemistry and Its Applications (TCCMA 2024)

Workshop Organizers

Noelia Faginas-Lago	University of Perugia, Italy
Andrea Lombardi	University of Perugia, Italy
Marcos Mandado	University of Vigo, Spain

Workshop Program Committee Members

Ángel Martín Pendás	University of Oviedo, Spain
Ernesto Garcia Para	University of Basque Country, Spain
Giovanni Bistoni	University of Perugia, Italy
Juan Jose Nogueira Perez	University Autonoma of Madrid, Spain
Jose Hermida	Universidade di Vigo, Spain
Luca Mancini	University of Perugia, Italy

Transport Infrastructures for Smart Cities (TISC 2024)

Workshop Organizers

Francesca Maltinti	University of Cagliari, Italy
Mauro Coni	University of Cagliari, Italy
Francesco Pinna	University of Cagliari, Italy
Chiara Garau	University of Cagliari, Italy
Nicoletta Rassu	University of Cagliari, Italy
James Rombi	University of Cagliari, Italy

Workshop Program Committee Members

Benedetto Barabino	University of Brescia, Italy
Martina Carra	University of Brescia, Italy

Mauro D'Apuzzo	University of Cassino, Italy
Roberto Minunno	Curtin University, Australia
Claudia Loggia	University of KwaZulu-Natal, South Africa
Amir Kavussi	Tarbiat Modares University, Iran
Tiziana Campisi	University of Enna Kore, Italy
Alessandro Plaisant	University of Sassari, Italy
Elena Cocuzza	University of Catania, Italy
Vincenza Torrisi	University of Catania, Italy

From Structural to Transformative-Change of City Environment: Challenges and Solutions and Perspectives (TRACE 2024)

Workshop Organizers

Maria Rosaria Guarini	Sapienza University of Rome, Italy
Francesco Sica	Sapienza University of Rome, Italy
Carmelo Maria Torre	Polytechnic University of Bari, Italy
Francesco Tajani	Polytechnic University of Bari, Italy

Workshop Program Committee Members

Angela Pilogallo	Italian National Research Council, Italy
Maria Cerreta	University of Naples Federico II, Italy
Giuseppe Cerullo	Sapienza University of Rome, Italy

Transport and Digital Multiscale Sustainable Network for Circular Economy (TransNet 2024)

Workshop Organizers

Andrea Gallo	University of Trieste, Italy
Mara Ladu	University of Cagliari, Italy
Enrico Dagostini	University of Malta, Malta
Salvatore Dore	University of Trieste, Italy
Martina Sinatra	University of Cagliari, Italy
Francesca Sinatra	University of Trieste, Italy

Workshop Program Committee Members

Martina Carra	University of Brescia, Italy
Ginevra Baletto	University of Cagliari, Italy
Giuseppe Borruso	University of Trieste, Italy
Beniamino Murgante	University of Basilicata, Italy
Maria del Mar Munoz Leonisio	Univeristy of Cadiz, Spain
Ahinoa Amaro Garcia	Univeristy of Las Palmas of Gran Canaria, Spain
Malgorzata Hanzl	Lodz University of Technology, Poland
Balázs Kulcsár	University of Debrecen, Hungary

Temporary Real Estate Management: Approaches and Methods for Time-Integrated Impact Assessments and Evaluations (TREAT 2024)

Workshop Organizers

Chiara Mazzarella	TU Delft, The Netherlands
Hilde Remoy	TU Delft, The Netherlands
Maria Cerreta	University of Naples Federico II, Italy

Workshop Program Committee Members

Maria Lucia Raiola	University of Naples Federico II, Italy
Eugenio Muccio	University of Naples Federico II, Italy
Daniele Cannatella	TU Delft, The Netherlands
Sabrina Sacco	University of Naples Federico II, Italy
Piero Zizzania	University of Naples Federico II, Italy
Stefano Cuntò	University of Naples Federico II, Italy
Sveva Ventre	University of Naples Federico II, Italy
Caterina Loffredo	University of Naples Federico II, Italy
Giuseppe Ciciriello	University of Naples Federico II, Italy
Maria Somma	University of Naples Federico II, Italy
Ludovica La Rocca	University of Naples Federico II, Italy
Laura Di Tommaso	University of Naples Federico II, Italy
Benedetta Grieco	University of Naples Federico II, Italy
Gaia Daldanise	National Research Council, Italy
Simona Panaro	University of Sussex, UK
Giuliano Poli	University of Naples Federico II, Italy

Urban Regeneration: Innovative Tools and Evaluation Model (URITEM 2024)

Workshop Organizers

Fabrizio Battisti	University of Florence, Italy
Giovanna Acampa	University of Florence and University of Enna Kore, Italy
Orazio Campo	La Sapienza University of Rome, Italy

Workshop Program Committee Members

Alice Barreca	Polytechnic of Turin, Italy
Marco Rossitti	Polytechnic of Milan, Italy
Celestina Fazia	University of Enna Kore, Italy

Urban Space Accessibility and Mobilities (USAM 2024)

Workshop Organizers

Chiara Garau	University of Cagliari, Italy
Alessandro Plaisant	University of Sassari, Italy
Barbara Caselli	University of Parma, Italy
Gabriele D'Orso	University of Palermo, Italy
Mauro D'Apuzzo	University of Cassino, Italy
Matteo Ignaccolo	University of Catania, Italy

Workshop Program Committee Members

Ivan Blečić	University of Cagliari, Italy
Mauro Coni	University of Cagliari, Italy
Martina Carra	University of Brescia, Italy
Tiziana Campisi	University of Enna Kore, Italy
Tanja Congiu	University of Sassari, Italy
Francesca Maltinti	University of Cagliari, Italy
Silvia Rossetti	University of Parma, Italy
Angela Pilogallo	Italian National Research Council, Italy
Lorena Fiorini	University of L'Aquila, Italy
Francesco Pinna	University of Cagliari, Italy

Aime Tsinda	University of Rwanda, Rwanda
Nicoletta Rassu	University of Cagliari, Italy
Youssef El Ganadi	International University of Rabat, Morocco
Marco Migliore	University of Palermo, Italy
Elena Cocuzza	University of Catania, Italy
Alessio Salvatore	Italian National Research Council, Italy
Giuseppe Stecca	Italian National Research Council, Italy
Gerardo Carpentieri	University of Naples Federico II, Italy
Carmen Guida	University of Naples Federico II, Italy
Floriana Zucaro	University of Naples Federico II, Italy

Virtual Reality and Augmented Reality and Applications (VRA 2024)

Workshop Organizers

Osvaldo Gervasi	University of Perugia, Italy
Damiano Perri	University of Florence, Italy
Sergio Tasso	University of Perugia, Italy

Workshop Program Committee Members

Massimiliano Nicolini	OliTec Foundation, Italy
JungYoon Kim	Gachon University, South Korea
Paolo Nesi	University of Florence, Italy
David Berti	ART SpA, Italy
Tamie Salter	Citizen Alert Inc., Canada
Marcelo Guimarães	Federal University of São Paulo, Brazil

Workshop on Advanced and Computational Methods for Earth Science Applications (WACM4ES 2024)

Workshop Organizers

Luca Piroddi	University of Malta, Malta
Patrizia Capizzi	University of Palermo, Italy
Marilena Cozzolino	Università Del Molise, Italy
Sebastiano D'Amico	University of Malta, Malta
Chiara Garau	University of Cagliari, Italy
Giuseppina Vacca	University of Cagliari, Italy

Workshop Program Committee Members

Andrea Angelini	ISPC, CNR, Italy
Raffaele Martorana	University of Palermo, Italy
Paolo Mauriello	University of Molise, Italy
Raffaele Persico	University of Calabria, Italy
Eufemia Tarantino	Polytechnic of Bari, Italy
Roberto Ricciu	University of Cagliari, Italy
Stefano Sfarra	University of L'Aquila, Italy
Peter Iregbeyen	University of Malta, Malta
Elisa Pilia	University of Cagliari, Italy
Emanuele Colica	Ministry for Transport, Infrastructure and Public Works, Malta
Luciano Galone	University of Malta, Malta
Sergio Vincenzo Calcina	University of Cagliari, Italy
Maria Brovelli	Polytechnic of Milan, Italy
Francesca Trevisiol	University of Bologna, Italy

Additional Reviewers

Burak Aslan	Izmir Institute of Technology, Turkey
Birim Balcı	Manisa Celal Bayar University, Turkey
Atrin Barzegar	Università degli Studi della Campania L. Vanvitelli, Italy
Manuel Carlos Figueiredo	University of Minho, Portugal
Chiara Chioni	University of Trento, Italy
Annalisa Contato	University of Palermo, Italy
Aurora Costales	Universidad de Oviedo, Spain
Hamid Daneshpajouh	Middle East Technical University, Turkey
Vito Dario Camiola	Università di Catania, Italy
Roberta De Fazio	Università degli Studi della Campania Luigi Vanvitelli, Italy
Michele Di Giovanni	Università degli Studi della Campania, Italy
David Ferro Costas	University of Santiago de Compostela, Spain
Michal Hnatič	P.J. Šafarik University in Košice, Slovak Republic
Francesco Loddo	Henge S.r.l., Italy
Caterina Loffredo	University of Naples Federico II, Italy
Vanda Lourenco	Universidade Nova de Lisboa, Portugal
Ángel Martín Pendás	Universidad de Oviedo, Spain
Maria Mourao	Polytechnic Institute of Viana do Castelo, Portugal

Martin Perez Perez	University of Vigo, Spain
Marco Pezzella	University of Perugia, Italy
Maria Polidoro	ESTG IPP, Portugal
Josef Rebenda	Brno University of Technology, Czech Republic
Donatella Rita Fiorino	University of Cagliari, Italy
Evgeniy Romenskiy	Sobolev Institute of Mathematics, Russia
Ezgi Sahin Toptal	Mersin University, Turkey
Domenica Savia Pellicanò	Mediterranean University of Reggio Calabria, Italy
Carina Silva	ESTeSL-IPL, Portugal
Paula Simões	CMA FCT UNL CINAMIL, Portugal
Francesca Sinatra	University of Trieste, Italy
Ana Sofia Rézio	Iscal, Portugal
Alexandra Stankulova	Politecnico di Torino, Italy
Maria Stella De Biase	Università della Campania Luigi Vanvitelli, Italy
Guan Yue Hong	Western Michigan University, USA

Sponsoring Organizations

ICCSA 2024 would not have been possible without the tremendous support of many organizations and institutions, for which all organizers and participants of ICCSA 2024 express their sincere gratitude:



Springer Nature Switzerland AG, Switzerland
(https://www.springer.com)



Computers Open Access Journal
(https://www.mdpi.com/journal/computers)



Thuyloi University, Hanoi, Vietnam
(https://en.tlu.edu.vn/)





University of Perugia, Italy
(https://www.unipg.it)



University of Basilicata, Italy
(http://www.unibas.it)



Monash University, Australia
(https://www.monash.edu/)



Kyushu Sangyo University, Japan
(https://www.kyusan-u.ac.jp/)

Universidade do Minho
Escola de Engenharia

University of Minho, Portugal
(https://www.uminho.pt/)

University of Cagliari, Italy
(https://en.unica.it/en)

Venue

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.

References

1. Vu, M., Thai, M.T.: PGM-explainer: probabilistic graphical model explanations for graph neural networks. In: Advances in Neural Information Processing Systems (NeurIPS) (2020)
2. Nguyen, T., Lai, P., Phan, H., Thai, M.T.: XRand: differentially private defense against explanation-guided attacks. In: AAAI Conference on Artificial Intelligence (AAAI) (2023)
3. Vu, N., Nguyen, T., Thai, M.T.: NeuCEPT: learn neural networks' mechanism via critical neurons with precision guarantee. In: IEEE International Conference on Data Mining (ICDM) (2022)

4. Conmy, A., Mavor-Parker, A., Heimersheim, S., Garriga-Alonso, A.: Towards automated circuit discovery for mechanistic interpretability. In: Advances in Neural Information Processing Systems (NeurIPS) (2023)
5. Vu, M., Nguyen, T., Jeter, T., Thai, M.T.: Analysis of privacy leakages in federated large language models. In: International Conference on Artificial Intelligence and Statistics (AISTATS) (2023)

Contents – Part III

Cities, Technologies and Planning (CTP 2024)

Understanding Climate Change in Alpine Region Through Geo-Referenced Multi-factor Mapping of Ski Facilities and Over-Tourism 3
Beatrice Citterio and Letizia Bollini

Methodological Approach for Classifying Typical Recurrent Urban and Peri-Urban Configurations 18
Chiara Di Dato

Renewables Energy Communities to Restore the City/Country Relationship: The Case of San Severo in the Apulia Region (Italy) 32
Michele Vomero, Antonio Leone, and Maria Nicolina Ripa

Potential of the 15-Minute Peripheral City: Identifying Main Streets and Population Within Walking Distance 50
Joan Perez and Giovanni Fusco

The Spatial Roots of Urban Growth: Modelling Urban Dynamics with Space Syntax 61
Federico Mara, Chiara Anselmi, Federica Deri, and Valerio Cutini

Public Participation in the 15-Minute City. The Role of ICT and Accessibility to Reduce Social Conflicts 77
Beniamino Murgante and Irina Di Ruocco

Downscaling Strategic EU Policy Directions in Mediterranean Cities: Participatory Assessment of Critical Issues and Barriers 93
Anastasia Stratigea, Yiota Theodora, and Chrysses Nicolaides

Communal Resilience Framework 112
Ondrej Mital', Silvia Ručinská, and Miroslav Fečko

Coastal Land Use Planning. An Integrated Approach Between Environmental Protection, Economic Competition and National Defense: The Case of Quirra, Sardinia (Italy) 131
Nicolò Fenu, Ginevra Balletto, and Giuseppe Borruso

Post-seismic Reconstruction Planning. A Space-Time Scheduling Multi-prospects Model 141
Maria Rosa Trovato, Ludovica Nasca, Vittoria Ventura, Salvatore Giuffrida, and Filippo Gagliano

The Urban Life Cycle in the Italian Demographic Winter. An Analysis on Metropolitan Cities 159
Giuseppe Borruso and Ginevra Balletto

National Spatial Data Infrastructure (NSDI) for Resilient Territorial Development: Building a National Disaster Risk Register (DRR) for Serbia 172
Ljiljana Živković

Serious Digital Geogames and Their Implementations Enhanced by Artificial Intelligence, Mixed- and Augmented-Reality 189
Alenka Poplin

Mapping Emotional Landscapes: Understanding the Interplay of Emotions and the Built Environment in Potenza, Italy 202
Beniamino Murgante, Giovanni Mazzarelli, Claudia Hedwig van der Laag Yamu, and Alfonso Annunziata

Application of the 15-Minute City Criteria to a Metropolitan Area: The Case Study of the Metropolitan City of Cagliari, Italy 218
Beniamino Murgante and Alfonso Annunziata

Computational Methods for Porous Geomaterials (CompPor 2024)

Numerical Modeling of Fluid-Saturated Porous Sample Loading Based on Thermodynamically Compatible System Theory 237
Mikhail Novikov, Vadim Lisitsa, and Evgeniy Romenski

Construction of Relative Permeability Curves by Numerical Simulation of Two-Phase Flow in 3D CT-Models 250
Tatyana Khachkova and Vadim Lisitsa

NDM-Net and Model Changes 263
Elena Gondyul, Kirill Gadylshin, Vadim Lisitsa, and Dmitry Vishnevsky

Effective Numerical Dispersion Suppression in 3D Seismic Modeling 276
Kirill Gadylshin, Vadim Lisitsa, Kseniia Gadylshina, and Dmitry Vishnevsky

Dependence of CO_2 Breakthrough on the Sorbent Packing 290
Alexandra Gonchar, Vadim Lisitsa, Tatyana Khachkova, Dmitry Prokhorov, and Vladimir Derevschikov

Solve the Quasi-static Biot Problem on Shared Memory Systems with Various Processors 305
Sergey Solovyev and Vadim Lisitsa

Computational Analysis of Seismic Waves Attenuation Caused by Porosity Variability in a Fluid-Saturated Porous Model of Thawing Permafrost 321
Galina Reshetova, Mikhail Novikov, and Evgeniy Romenski

Simulated Annealing Algorithm for Model Reconstruction of the Four-Layer Medium with Elliptical Inclusion in the Third Layer 334
Dmitry Prokhorov, Galina Reshetova, and Denis Bratchikov

Reducing Numerical Dispersion in Pseudo-3D Space and Constructing Training Dataset 352
Elena Gondyul, Kirill Gadylshin, Vadim Lisitsa, and Dmitry Vishnevsky

Sustainable Digital Circular Economy (DiCE 2024)

Integrating Territorialization, Circular Economy, and Industrial Symbiosis: Leveraging GIS for Enhanced Efficiency in Industrial Zones 369
Francesca Sinatra, Giuseppe Borruso, and Sandra Primiceri

Smart City-Port Relationship: A Circular Port City Development Model for Trieste 384
Giuseppe Borruso, Andrea Gallo, Francesca Sinatra, Ginevra Balletto, and Salvatore Dore

Investigating the Relationship Between Land Use and Wealth in Italian Provinces 401
Giuseppe Borruso, Andrea Gallo, Francesco Magris, and Nicola Pontarollo

Author Index 413

Cities, Technologies and Planning (CTP 2024)

Understanding Climate Change in Alpine Region Through Geo-Referenced Multi-factor Mapping of Ski Facilities and Over-Tourism

Beatrice Citterio[1] and Letizia Bollini[2(✉)]

[1] Università degli Studi della Campania Luigi Vanvitelli, 81100 Caserta, CE, Italy
[2] Free University of Bolzano, 39100 Bolzano, BZ, Italy
letizia.bollini@unibz.it

Abstract. The exponential growth of winter tourism, which in the central-European Alpine Region is inseparable from the rise to mass practice of Alpine skiing, has fundamentally reshaped leisure practices and the Alpine landscape, transitioning from a recreational pursuit to a multi-billion dollar industry [1]. This evolution necessitated landscape modernisation efforts, with stakeholders including skiers, supply companies, local and foreign investors, regions and states collaborating to tailor the Alpine environment to skiing needs, fostering a predictable and profitable industry [2]. This transformation made a previously feared environment profitable and laid the foundations for the economic development of entire valleys [3]. However, it has not been without consequences. While intended to facilitate growth and profitability, interventions and technologies have paradoxically diminished skiing's appeal to specific segments of society due to the intense exploitation of natural resources, including landscape, which appears to be the most noticeable casualty [4]. This paper explores the ongoing changes in Italy's Alpine and Apennine regions, tracing the transition from landscape modifications for infrastructure development to contemporary challenges driven by structural abandonment, exacerbated by climate change and inadequate management practices [3]. Utilising a multi-practical approach, including visual aids such as maps and aerial photographs, this research aims to offer accessible insights into the phenomenon of mass skiing in Italy, shedding light on its historical trajectory, socio-economic impacts, and current challenges.

Keywords: Mass Ski Tourism · Climate Change · Alpine Regions · Georeferenced Data · Over Tourism · Rural Development

1 Mountain Mass Tourism and Anthropization

Extreme weather conditions, due to climate change, bring changes to environments and biodiversity together with inevitable transformations in social, economic, and political dynamics [5]. These conditions often manifest and are enhanced by power distribution problems, new forms of social inequality and a broad diversification of opportunities. In addition, changes in the technological landscape, new energy relations and the introduction of new technologies are being witnessed and experimented [3]. Within this

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 3–17, 2024.
https://doi.org/10.1007/978-3-031-65238-7_1

framework of tension and restlessness contradictions, among many others, the issue of the economic, social and environmental sustainability of winter alpine tourism takes up ample space, also considered high mountain areas being the most affected by climate change [6].

The exponential growth of winter tourism, mainly through alpine skiing, has brought about significant changes in leisure practices and the alpine landscape since the 1930s, transforming this once widely popular recreational activity into a multi-billion dollar industry [3]. By the end of the 20th century, the Alps housed approximately 12 million residents but welcomed tourists at least ten times more annually [7]. Due to its magnificent landscape, steep and challenging terrain, high levels of snowfall, and proximity to European metropolitan areas, the Alpine region was particularly suitable first for health and healing trips for the urban upper middle class and then for downhill skiing, born and promoted as an expression of the futurist values of speed, impulse, a relationship with nature and a holiday from hectic urban life [2]. This process of adaptation to tourist skiing, however, has not been painless: European ski resorts, decade after decade, have become more and more products of human management and manipulation of the alpine landscape, mass-oriented architecture and leisure-led development, continuously promoting human interventions involving cutting, filling, excavating, building and finally reaching the point of artificial snow production [7].

Certain Alpine regions have gradually transformed into monocultural landscapes dedicated exclusively to winter tourism, resulting in expansion and overcrowding [7]. This shift has led to a gradual gentrification of these areas, manifested in the displacement of the local population, which has been replaced by temporary, seasonal tourists and profit [3]. Supported by an economic inducement in the hands of a few but closely linked to the ruling class of the various regions, it has reached the semblance of a veritable Alpine skiing lobby [7].

It is worth noting that the romanticised image of alpine skiing before mass tourism and the pre-intense skiing era overlooks the complex interplay between humans and nature. It presents a reality that appears increasingly distant from the mountain landscape and ecosystems and the actual socio-economic situation. Regardless of this and the actual climate situation, romanticised images of mountain landscapes and the promise of abundant snowfalls are still used as the main content for advertising and promoting winter holiday destinations [3].

As stated by Nardelli and Dematteis [7] in their book Inverno Liquido, for quite a long time, the mountains supplied the cities with minerals, building stones, timber, meat, milk, cheese, hydraulic and electric power, and labour functions that are still present today but with much less importance than in the past. The mountain and the city used to be much more explicitly interdependent, a feature that today has been blurring mainly in communication rather than reality. The mountains were and are a place of hard work, harsh rhythms, and climate, which have always forced the people living there to adapt. As Maya Ishizawa [8] states in her thesis, “Even though “life in the mountains is tough”, this way of life forms communal values, making mountain communities resilient. These essential principles of community are fundamental for sustainability and make mountain populations the most suitable to adaptation.”

In contrast to this context, from the 18th century onwards, the mountain became an object of the urban imagination. The needs it satisfies are no longer linked to local production but to the leisure time of citizens [3]. The communities living in the mountains adapted to these new demands, radically modifying their productive structure, welcoming holidaymakers, building health facilities such as sanatoria, places where they could offer relaxation, cures, and cosmetics, proposing mountaineering and hiking routes to reach the peaks, inventing professions to welcome, feed and guide guests that represented the prodromes of modern mountain tourism [9] (Fig. 1).



Fig. 1. The Dolomites, as illustrated in three advertisement manifestos from around 1935.

Following this path of shaping and constantly implementing the urban vision of the mountain environment in the construction of the tourism industry, the mountains become elective places for recreation and entertainment, where a semblance of an unspoilt natural landscape remains just for the citizens' eyes [9], and the agropastoral and rural production and economic system quickly fade into the background.

Analysing the topic of mountain mass tourism through the definition of "Monoculture of Skiing" therefore adds a layer of interpretation to the research, significantly expanding the scope of the satellite themes and highlighting the socioeconomic, anthropological, and political implications of such a transition [3]. In anthropology and ethnology, monoculture refers to the process of cultural homogenisation resulting from historical and social factors, wherein diverse traditions and ideologies converge towards a unified cultural model that diminishes the distinctions among their original components. This convergence often leads to the dominance of a simplified or standardised cultural framework. However, monoculture can also manifest inflexibly, disregarding the complexities and variations inherent in the original components [10].

Framing the ski industry as 'monocultural' is indispensable when seeking solutions for mitigation and adaptation to the climatic and economic future looming over mountain areas. A more moderate and less widespread type of practice would require less radical approaches while having such a developed, capillary, monocultural industry leads the problem actors to the near impossibility of imagining alternatives. For this reason, new technologies for adapting to climatic conditions and new infrastructural development plans conceived even decades ago continue to be implemented, testifying to a system that sees no future but only the present and the past.

By interpreting the ski industry as a monoculture, the research exposes the pervasive growth processes of a seemingly recreational activity that has come to dominate entire valleys, creating economic dependencies that are challenging to overcome (Fig. 2).



Fig. 2. Hotel Nevada is an abandoned accommodation facility for skiers near the slopes. Monte Bondone, Trento (TN) Italy, photographed June 2023.

The repercussions of the mass skiing industry on local communities and environments are continuously being discovered, particularly when scrutinised through an informed lens. For instance, the reliance on the monoculture of tourism has resulted in the gradual marginalisation of traditional sectors of the local economy. This is partly due to the challenges supply chains face integrating with the logic of hotel chains and algorithms that tend to homogenise offerings [3].

Consequently, there has been a gradual detachment from the local territory as a living space while the emphasis shifts towards sustaining the ski industry, which remains seasonal. The result is a flattening of economic incentives, the convergence of local businesses towards the sustenance of ski activities, the expansion of accommodation facilities, and the homogenisation of culinary and experiential offerings in favour of what is labelled as 'traditional' [7]. The fossilisation of most of the economic input on a single tourism practice developed on a weather event (snow) that is not seasonally predictable and, in recent years, subject to intense alterations and peaks, creates an extremely fragile socioeconomic structure [7]. As an example of some areas' risk of economic reliability and socio-economic sustainability, the dataset compiled by the Dislivelli association encompassed 563 municipalities in the Western Alps (Piedmont, Aosta Valley). The research findings indicated a pronounced disparity in financial outcomes between municipalities focusing solely on snow tourism and those embracing diversifying their offerings to tourists. Specifically, the analysis revealed an average loss of 89.8 million euros per municipality, characterised by a mono-functional approach, compared to an average loss of 47.8 million euros among municipalities that exhibited

a diversified range of services [11]. These findings underscore the significance of diversification as a strategic approach for enhancing economic resilience within mountain tourism. Ultimately, due to monocultural management, the connections to the specific localities erode. The narrative thread aligns season after season, country after country, culminating in large ski complexes such as Dolomiti Superski (Trentino-Alto Adige, Veneto, IT), La Via Lattea (Piedmont, IT), or Monterosa Ski (Aosta Valley, Piedmont, IT) (Fig. 3).



Fig. 3. The report from Legambiente, 'Neve Diversa' (Legambiente, 2023), shows the number of artificial reservoirs in each region of Italy, from 0 to 60.

To give an idea of state investments without which the Italian ski industry would be able to sustain itself due to the very high operating costs and the intricate network of profit distribution, it is interesting to report one of the latest governmental measures: the Italian Ministry of Tourism alone has allocated more than 200 million euro 'for the modernisation, safety and decommissioning of ski lifts and snowmaking facilities' for the two years 2024–2026 alone, the year in which, not coincidentally, the 2026 Winter Olympics Milan Cortina will take place in Italy [12]. This money do not comprehend annual and seasonal investments from regions alone and spot-investment from the central government.

Considering all the above, if we now shape the problem around balancing economic prosperity and environmental conservation, we will find another big issue in this industry, which is strictly linked with its economic profit-led system and interlinked with its social, economic, and political levels (Fig. 4).

The phenomenon of mass winter tourism in Italy and the proliferation of ski facilities and resorts from the boom years of the snow industry up to now have had a significant impact on the architecture and landscape of the Italian Alps, starting from the development of facilities dating back to the 1960s–70s–80s which led to the installation of numerous invasive ski resorts at very low altitudes, even at less than a thousand metres



Fig. 4. Via Gioia, next to Piazza Gae Aulenti, Milan, Italy, 2023.'Piles of Snow and 'Winter with a Bang' are in the Airbnb advertising winter campaign.

above sea level [2]. With the continuous rise in temperature and the general harmful redistribution of snowfall in recent decades, this factor, through the progressive rise of the snow reliability line, is causing more and more closed, disused or abandoned ski areas to emerge. Some of these areas, once alive with activity and the daughters of a playful spirit that is now anachronistic, now stand as silent witnesses to poor management practices and the climatic challenges faced by the ski industry [7]. If the lower ski areas are not being abandoned, it is because of public money given by provinces, regions and the central government to create adequate intensive infrastructure to provide artificial snow: the 2024 Nevediversa Report [13] from Legambiente states that that the number of snowmaking reservoirs in Italy is 158, 16 more than 2023. Artificial water storage lakes - from local rivers and streams - are indispensable for creating artificial snow, which in Italy is used to make snow on more than 90% of its ski slopes [13].

Based on this data, this research represents a geo-referenced mapping of Italian ski areas, divided into active and non-active ones. This geo-referenced snapshot of the current state of the ski industry in Italy was made possible by using qualitative and quantitative data from online blogs [15], official reports [13, 14], literature, and editorial texts. Through the analysis of these sources, an attempt was made to gain a deeper understanding of the current situation in the Alps, shedding light on this widespread phenomenon and its implications and, most of all trying to offer a way of portraying them through an easily accessible and understandable medium.

It is imperative to acknowledge that the following representation of reality is predicated upon an extensive array of sources, albeit with specific applicability limited to the Italian Alps and, to a certain extent, the Appenini mountain region.

While it is true that diverse values and characteristics characterise different Alpine regions and their touristic management [8], the aim of this study lies first in a punctual depiction of reality and, most of all, in developing a methodological framework that - given the lack of data on the subject - tries to combine all available resources drawing upon archival data, online citizen science platforms, and reports.

By leveraging these resources, one of the aims is to facilitate and augment mapping endeavours spanning the entirety of the Italian Alps and Appennini and extend this approach to encompass a more comprehensive understanding and analytical examination. With this tool being managed by single individuals, it could be a very interesting base to enhance citizen-based collaborative processes, filling the gap between scarce administration communication of monitoring and reality.

Citizen-based collaborative approaches, as advocated by Legambiente within their Nevediversa 2023 report [14], would entail active engagement with local communities, thus engendering a more nuanced and context-specific exploration of the subject matter at hand, hypothetically enhancing a first-step acknowledgement of reality and, further, decisionmaking (Fig. 5).



Fig. 5. Seiser Alm, access to the slopes covered in mud, photographed the week after the end of the ski season, meaning without continuous artificial snow. April 2023.

1.1 Geo-Referenced Mapping of Italian Mountain Ski Areas

Examining the geographical distribution of skiing facilities in Italy offers a comprehensive insight into the extensive prevalence of this recreational pursuit. Consequently, one can discern the extent of the socio-economic significance of the ski monoculture, underscoring its pivotal role in sustaining entire valleys as a primary economic driver. This analysis elucidates the inherent socio-economic risks associated with a potential cessation of skiing activities and the concomitant disappearance of the sport, a consequence of the ongoing climate change and the precipitous escalation in temperatures [13].

Such research also highlights the profound implications for environmental management and conservation policies. It is imperative to address the environmental and landscape-related implications of such a future-blind investment machine, which, is frequently applied even to protected areas [13], proving the extent of such a profit-led and competitive sector.

As part of the qualitative and quantitative research, it was decided to include a quantitative geographical and geo-referenced cloud of the distribution of ski facilities in Italy to provide a direct visualisation of the problem and, above all, to provide a monitoring basis for research. Aside from this, a qualitative analysis was conducted using satellite top-views of the areas considered. It is important to notice that this database must be updated frequently due to rapid environmental changes and the consequent impact on the opening and closure of ski plants related to snow reliability and available vital liquidity. To better explain and understand the method, the steps and sources that were used and went into creating the final result, three sections explain the process step by step (Fig. 6).

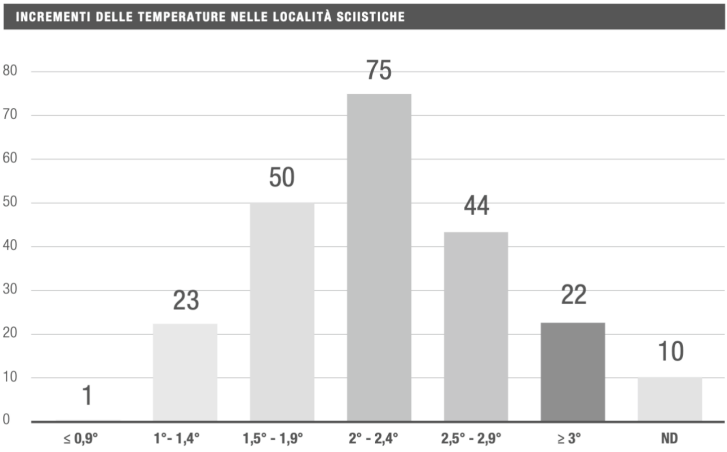


Fig. 6. Legambiente elaborates on temperature increases from 1961 to 2018 in Italian mountain municipalities in or near ski resorts, based on data https://climatechange.europeandatajournalism.eu/it/map. (Legambiente, 2023)

The software chosen map each location was Google Earth. Using Google Earth for mapping proved significant, enabling deep top-view analysis of the territorial transformations associated with ski area development and post-development phases. These alterations encompass deforestations taking on a corridor-shaped configuration, the emergence of commercial structures, the specific presence of artificial lakes next to ski plants, and the systemic reorganisation of the overall territory, including edification projects [7]. This visual evidence was important for research and delivery reasons since it has proven to be a strong visual tool to show the depth of the modification in these territories, making all the data more evident, reality-linked, and therefore graspable to a broader and more varied public.

Moreover, by looking at specific ski areas, both on pins and in visual top views, it is possible to identify patterns and factors that have either enhanced their current activity or contributed to their decline, providing a relative understanding of the challenges faced by the ski industry. In the eyes of those who want to see, this analysis provides a critical basis for anticipating pessimistic repetitive developments [13] and investments or assessing the potential for a disruptive, positive management shift in these areas.

1.1.1 Geo-Referenced Mapping Method and Criteria

The approach adopted to map the Italian ski areas in the northern, central, and southern regions, including the Alpine and the Appenini regions, has been multi-factor.

For example, the mapping includes data obtained through online archival research [13, 14], regional datasets [13], and spontaneous citizen science [15], as well as in-person research visits and research.

Regarding the technical distribution of the data in question, the map's pins were divided into sub-sections for communication and research reasons. Firstly, two large datasets were created: one corresponding to the existing and active ski areas and the other representing the existing but inactive or abandoned ones. Each of these two sets of geographical coordinates was, in turn, divided into 21 sub-areas, i.e. by regions of Italy. By doing this, considering the high degree of multilevel diversity between one Italian region and another [16], it was also possible to visualise the different distribution of ski facilities according to region.

Regarding the two-group classification, the mapping criteria must be specified to understand why a location is considered in one group, the other, or none. The limitations of the interpretation criteria may emerge when looking for a definition of 'open', 'abandoned', or 'closed'. In such a case, the interpretation may seem blurred when applied to a variable context, like seasonal openings.

In the case of open facilities, references are made to complex ski areas grouped under a general name, such as location and pin. Under one pin, there might be multiple chair lifts or cablecars, depending on the area's infrastructuralisation. The name refers to the generally called location (e.g. the ski area of Foppolo has multiple chair-lifts, but just one pin is shown).

On the other hand, in the case of abandoned or closed lifts, the pin represents only single or multiple lifts that are not affiliated with other lifts that are still active are included. Therefore, it is important to note that ski lifts or chairlifts that have been closed, perhaps due to lack of snow or limited altitude, are not included in the mapping of abandoned or closed lifts if they belong to a larger area that is still functioning, that therefore could be listed under a pin in the map of the still open ones.. This methodology may not accurately reflect the presence of lifts no longer in operation within active ski areas but it was the best that could have been done with the time and resources given. Moreover, fieldwork investigation, walkscapes and Photoscape experiences, together with satellite top-views and further blog research, confirm that several closed plants may be under the jurisdiction of other still operating districts or that could have been bought and implemented by bigger ski areas to enlarge their ski area [7]. All these considerations support the difficulty of finding specific and clear data within the Italian ski areas.

1.1.2 Geo-Referenced Mapping Sources

The data required for mapping ski facilities was gathered through various channels, constituting a mix of sources across multiple platforms. This diverse dataset includes information on both active and inactive plants. It is essential to distinguish between data related to active lifts, which are readily available due to the direct interest of ski resorts and tourism offices, and data concerning abandoned or temporary-closed ski plants, which is often less known, even among regional mobility and tourism offices. This separation is crucial for a comprehensive understanding of ski facility infrastructure, especially considering the limited awareness surrounding inactive lifts within regional authorities and little management and investments for their re-naturalization.

For this reason, forms of citizen activism, personal contributions, and partial censuses from people interested in the topic or participants in activist movements had to be used to map the inactive section of ski-plants.

This glaring lack of data in the regional archives concerning disused facilities highlighted an underlying problem in their management: the lack of transparency, attention and post-use protection, and, as said, the lack of attention to dismantling and natural regeneration of the areas affected by disuse. If something is not documented or discussed, it is difficult to affect future decision-making.

As said before, the data inherent to non-active plants came from various sources, including personal testimonies, forums and dedicated websites documenting the state of disused ski areas. The most consulted blog was a website called www.skiforum.it [15]. On this amatorial ski-fan-based online platform, users have been tracking several disused facilities in the Alps and Apennines for years through memories, historic photo sharing, and online discussion with data from all over Italy. These first-hand experiences and observations have provided valuable insights into these abandoned areas' locations, history, and status. Complementing the data from the online blogs, official reports such as Legambiente's 'Neve Diversa' [13, 14] and other reports from previous censuses by associations such as Mountain Wilderness [17] offered further authoritative help in mapping and raising awareness of the current state of the problem. Beyond the non-active areas, the reports provided extensive data also on the second layer of mapping, meaning those still in operation and others referred to as 'cases of therapeutic obstinacy' [13, 14], which means ski plants in which the money input overflows the seasonal income wisely.

1.1.3 Geo-Referenced Mapping Process

The project began by acknowledging the necessity of systematically incorporating numerous location points into a map. Following this, a strategic decision was made to divide active and abandoned ski facility layers into 21 distinct regional sub-divisions. This segmentation was essential to avoid logistical challenges and maintain organisational coherence when mapping the pins within a broader geographical context. The first layer of pins made was the one regarding the closed areas, followed, just later, by the one of the existing and active ones. The process started, therefore, with gathering data regarding abandoned and closed ski areas and triangulating data from citizen science approaches by one specific online blog and three papers by Legambiente and Mountain Wilderness [17]. The mapping started on Google Earth, which made it possible, together

with the pinning, to analyse the territory and relative modifications and peculiarities of different abandoned ski areas from a top-view visual perspective. Therefore, the abandoned and active ski plants have been mapped in Google Earth, region after region, and shaped into a KML File. upon generating the KML file in Google Earth, the objective was to render the project accessible and shareable to the public via an open-access, browser-searchable map. However, during the upload of the pins on Google Maps, a significant obstacle was encountered, stemming from the limitations of My Maps, a platform within the Google ecosystem. Importing the KML file from Google Earth into My Maps posed a challenge due to restrictions on the number of points allowed for importation. consequently, in light of the extensive point data in both maps, it became necessary to create two partial maps. Notably, these partial maps exhibited a notable dearth of points, particularly about Southern Italy. A hypothetical methodology involving the sequential selection of points based on their chronological order of insertion was adopted regarding the arrangement of points on My Maps. Consequently, points originating from northern regions, being inserted first, were prioritised, while pins corresponding to southern regions, inserted subsequently, were excluded from the final presentation. At the same time as fixing the points on the map, an analysis of the location was carried out in parallel, employing bird flights and screenshots. This was mainly made possible by using Google Earth, which is integrated into the software, among others, photography, terrain analysis, and measurement commands.

1.2 Results

The mapping offers an insightful overview of downhill skiing in Italy, highlighting its widespread presence across the Alpine and Apennine regions. Notably, the sport's diffusion extends even to areas typically associated with maritime and summery activities, such as Sardinia and Sicily. This geographically comprehensive perspective provided by the mapping serves as crucial support for a narrative that often relies on complex scientific data, facilitating comprehension for a diverse audience.

The comparison between the general mapping of skiing facilities and aerial photos from Google Earth reveals distinct patterns within each location, particularly in active areas. These patterns include corridors dedicated to slopes, water reservoirs, artificial snow structures, ropeways, and a dense array of public and private reception facilities such as Airbnb, hotels, holiday homes, bed and breakfasts, winter sports shops, rentals, and restaurants. These features are typical of ski areas [7], and if compared between high-season and low-season periods, they express with critical precision how these locations have evolved towards the expression of what Marc Augée defines as 'non-places' [18], further interpretable as transitional landscapes. One evidence of this is the label 'temporarily closed' showing in every third sector service based in this area for two months before and after winter, representing the low season (Fig. 7, 8, 9, and 10).

1.3 Evaluation

The mapping process constituted a segment of a broader research endeavour, limiting the time available for its execution and preventing a thorough exploration of the complexities involved. Therefore, the maps offer a previously lacking general overview, serving as a

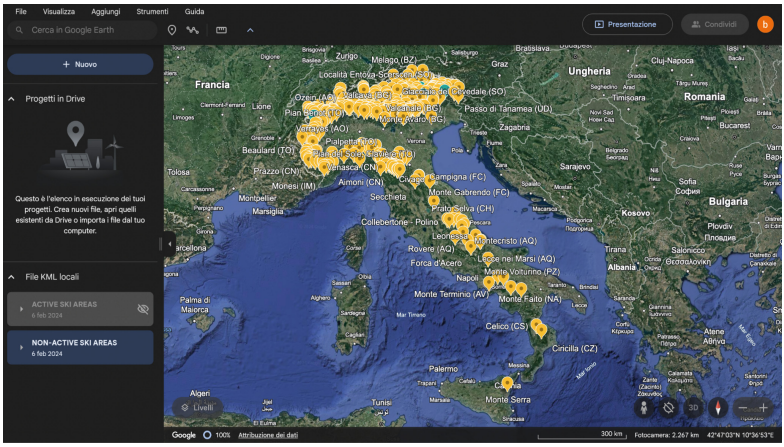


Fig. 7. Sneakpic of the mapped Abandoned Ski Areas in Italy on Google Earth (complete). Every pin is linked to the province to which it belongs. MyMaps version (incomplete due to the software's limited number of pins) is accessible here Non-Active Ski Areas, Italy (Mapped 2023).

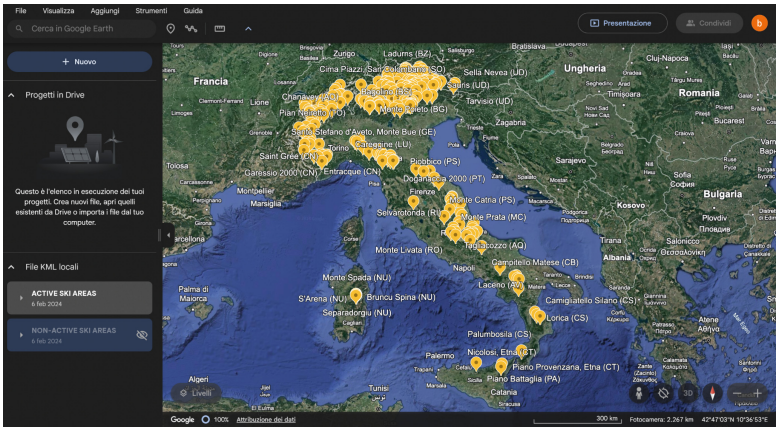


Fig. 8. Sneakpic of the mapped Active Ski Areas in Italy in Google Earth (complete). Every pin is linked to the province to which it belongs. The MyMaps version (incomplete due to the software's limited number of pins) is accessible here: Active Ski Areas, Italy (Mapped 2023).

foundation for interpreting a more intricate and non-visual dataset encompassed in the overall research.

Reading the results in this light, the primary objective - to make a more complex search visually comprehensible - has been achieved. Given the semi-collective nature inherent in the delineation of 'abandoned' sections within the mapping, it is underscored that the representation provided is not entirely exhaustive. This limitation arises from the dearth of comprehensive data sources, save for a handful of dated censuses with a degree of official vagueness.

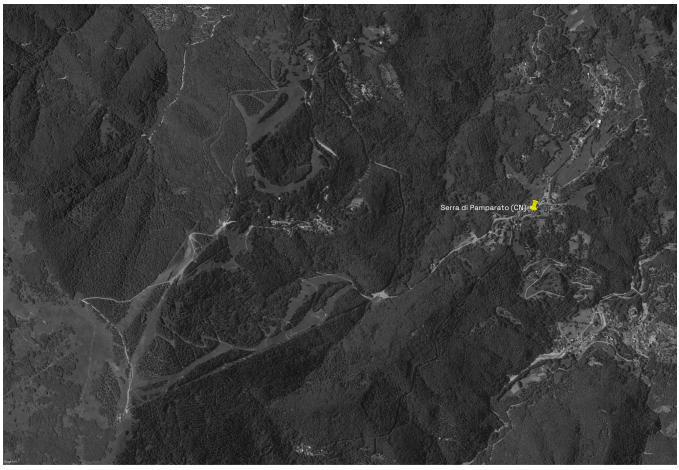


Fig. 9. Example of one of Google Earth's top views of the active ski areas representing Arabba's Ski Area (BL), Veneto, Italy. The intense use of artificial snow and the linked artificial reservoirs are highly visible.



Fig. 10. Example of one of Google Earth's top views of the non-active ski areas representing Serra di Pamparato (CN), Piedmont, Italy. The intense territorial modification the persistence of compacted snow on soil and artificial snow is still very visible even after the closure of the ski plant.

The dissemination and documentation of such locations are largely contingent upon voluntary and sporadic contributions, reliant upon the engagement of specific individuals within particular locales. For instance, anecdotal transmission and oral tradition play a significant role in identifying numerous disused areas that may not be represented on the map. Additionally, certain decommissioned installations exhibit ambiguous associations with adjacent operational facilities, rendering it challenging to ascertain their alignment

with the mapping criteria established by the community discourse. It is imperative to highlight that, concerning abandoned installations, the mapping criterion adheres to the guidelines delineated within the Skiforum [15] sharing blog, owing to the exigencies and practicalities of incorporating highlighted locations. Nonetheless, a supplementary mapping initiative encompassing all stationary installations, including those affiliated with parent facilities and consequently omitted from the current map, would prove beneficial and pivotal in advancing research.

A more detailed and accurate mapping exercise, particularly regarding abandoned plants, could have been conducted with additional time and resources. Moreover, increased resources and time facilitated the involvement of a larger research team, allowing for a more comprehensive and precise system of data mapping and interpretation.

Another point to emphasise is how, during the research, due to ignorance resulting from lack of experience in the field of mapping or due to limitations attributable to the software used, problems were encountered that made the reception of data from an external audience complex. About this, it must be mentioned that going from a dataset of coordinates from Google Earth and wanting to insert it into a publicly usable map on MyMaps, a service also offered by Google, limits were encountered in the number of points that could be imported: the map published on MyMaps is therefore deprived of part of it. This mapping process, both in its source form and ultimately in its outcome, however exhaustive for the research that was carried out, confirms how such an exercise carried out collectively and especially with a pool of multi-practice experts would achieve much more complex and comprehensive results.

1.4 Possible Developments and Implementations

Since the mapping process took place in a short period, and because of the fast-moving opening and closing situation as a result of the uncertain and pessimistic climatic situation, it is certainly possible to improve the project by implementing the mapping with an automatic update system that adds or subtracts locations in real-time. However, this is considered a complex and, above all, not a short-term step since, as it is also a data triangulation job, this update would require linking the mapping to a database in which someone would report the status of the ski resorts or in which each resort could declare its status.

Given the difficulties encountered in data retrieval, this implementation option is currently immature. Therefore, a more precise, independent and non-automated mapping of the resorts would be more appropriate and a possible next step. In light of this, opening the research as a shared database for the public and local inhabitants would be a strategic choice. Once more precise data has been obtained, after automating the data collection mechanism and localities' status, a further step would be to subdivide localities by extension to highlight their impact on the territory, the economy, and the infrastructural aspect. Finally, in addition to the two sections of 'open' and 'closed', we would like to implement a third section, called 'new investments' to shed light on all those resorts that benefit from current public or private investments and use the money to create new facilities, finance new ski services and/or feed their interests.

This, despite the extreme difficulty of finding much data on the subject, would complete an important research cycle and provide additional and indispensable foundations for understanding the phenomenon. Therefore, adding a third section to the map is considered the most important implementation to go further with.

References

1. Bartaletti, F.: Le grandi stazioni turistiche nello sviluppo delle Alpi Italiane. Pàtron (1994)
2. De Rossi, A.: La costruzione delle Alpi. Il Novecento e il modernismo alpino (1917–2017). Donzelli (2016)
3. Ferrari, M.A.: Assalto alle Alpi. Einaudi (2023)
4. Fischer, A., Adolf, H., Bender, O.: Are the skiing industry, globalisation, and urbanisation of alpine landscapes threatening human health and ecosystem diversity?. In: Nishi, M., Subramanian, S.M., Gupta, H. (eds.) Biodiversity-Health-Sustainability Nexus in Socio-Ecological Production Landscapes and Seascapes (SEPLS). Satoyama Initiative Thematic Review. Springer, Singapore (2022). https://doi.org/10.1007/978-981-16-9893-4_8
5. Gretta, T.P., et al.: Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. Science **355**, eaai9214 (2017)
6. Beniston, M., Diaz, H.F., Bradley, R.S.: Climatic change at high elevation sites: an overview. Climatic Change **36**(3) (1997). Springer
7. Nardelli, M., Dematteis, M.: Inverno Liquido. DeriveApprodi (2023)
8. Ishizawa, M.: About the conservation of cultural landscapes: sustainability or unviability? A comparative study on the emergent landscape management in heritage sites in mountain regions: the Andes and the Pyrenees. Ph.D. diss., BTU Cottbus-Senftenberg (2014)
9. Pioletti, A.M.: Benessere e turismo: un binomio importante per l'economia valdostana. GEOTEMA **39** (2009)
10. Hynes, M.: The Social, Cultural and Environmental Costs of Hyper-Connectivity: Sleeping Through the Revolution. Emerald Publishing, Bingley (2021)
11. Il turismo in montagna cambia pelle?. https://www.dislivelli.eu/blog/il-turismo-in-montagna-cambia-pelle.html
12. Ministero del Turismo. https://www.ministeroturismo.gov.it/montagna-santanche-investimenti-di-oltre-250-milioni-per-le-montagne-italiane/
13. Legambiente: Neve Diversa, il turismo invernale nell'era della crisi climatica (2024)
14. Legambiente: Neve Diversa, il turismo invernale nell'era della crisi climatica (2023)
15. Skiforum. https://www.skiforum.it/board/index.php?threads/36611/
16. Casaburi, A., Alberico, I., Matano, F.: Geodiversity of Italy. J. Maps **20**(1) (2024). https://doi.org/10.1080/17445647.2024.2340988
17. Mountain Wilderness, Censimento Impianti Abbandonati Lombardia 2007 (2007). chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.mountainwilderness.it/wp-content/uploads/2017/02/Impianti-abbandonati-Lombardia-2007.pdf
18. Augé, M.: Non-places: Introduction to an Anthropology of Supermodernity. Verso, London; New York (1995)



Methodological Approach for Classifying Typical Recurrent Urban and Peri-Urban Configurations

Chiara Di Dato(✉)

Department of Civil, Building-Architecture and Environmental Engineering, University of L'Aquila, Via Giovanni Gronchi 18, 67100 L'Aquila, Italy
chiara.didato@univaq.it

Abstract. Qualitative characterization of urban and peri-urban areas is widely studied in literature and definitions varies by geographic areas and specific characteristics. The paper aims at presenting a methodology to distinguish urban and peri-urban representative configurations by the means of artificial soil data, satellite images and qualitative interpretation of urban elements. The obtained classification covers 6 classes of 2 square-km recurrent configurations that are functional to the purposes of the integrated project LIFE IMAGINE Umbria, which aims at protection of habitats, biodiversity and local communities related to the Natura 2000 Network in Umbria region (Italy). The case study area is composed of two Functional Urban Areas: Perugia and Terni. The obtained results have already been supportive of planning strategies related to the project's outputs. The paper aims to approach and discuss the methodological approach in relation to its main scope in the LIFE IMAGINE Umbria project and to future developments and applications.

Keywords: peri-urbanization · urban morphology · Natura 2000 Network

1 Introduction

In the globalized world, cities are pole of economic growth, job and a variety of services and activities. The interest around cities and their expansion is even vivid because urban settlements have never stopped growing [1].

Increasing urbanization affects multiple fields related to the living and quality of spaces. Often, such process of urbanization consists in creating new peri-urban areas that deeply impact also on landscape fragmentation. Peri-urban areas can relate with socio-economic processes [2] and with quality of life [3] and quality of morphological configurations [4]. Also, peri-urbanization is directly related to processes that impact on ecological connectivity and environmental fragmentation. Ecological functions within adjacent natural and semi-natural areas can be highly compromised when they are "cut off" by new settlements and infrastructures [5].

The LIFE IMAGINE Umbria (LIFE19 IPE/IT/000015) [6] integrated project is devolved to implement the environmental continuity in Umbria region (central Italy). It

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 18–31, 2024.
https://doi.org/10.1007/978-3-031-65238-7_2

is 7 years long LIFE project started in 2020. The main object is the Natura 2000 (N2K) Network as established by the "Habitat" Directive 92/43/EEC [7]. The main goals are divided per actions, and they aim at the biodiversity conservation due to the creation of an integrated management system.

The Umbria region is around 8500 km^2 wide, whereas the extension of N2K network is around 1275 km^2 (around 15% of the regional territory). Then, the A2 action "Preliminary analysis of urban and peri-urban areas" has been focused on analyses of types of settlements for evaluating their role in conservation goals [8]. The action has been conducted with steps that included description and recognition of different recurrent urban and peri-urban areas; the analysis of existing and potential relationships with N2K networks' sites and then to the definition of guidelines devolved to evaluation processes of programs, plans and projects.

To this extent, classifying various types of settlement and defining proper differences between urban and peri-urban areas can be fundamental to assess environmental continuity with proper actions and projects.

In the fields related to management of cities no one approach can fully describe the nature of peri-urban dispersed configurations [9]. Researchers found out diverse methods and instruments for delimiting and classifying peri urbanization producing a multitude of contributions and prospectives [10, 11].

In many studies the peri-urban areas consist of very variable low-density urban morphology, multifunctional territories, and long commuting distances [12, 13]. Some analyses are focused on developing models and indicators for configuring and parametrize urban dynamics. The phenomenon's measure is considered crucial for having awareness of the problem. In the European context, settlement spread studies are associated with urban sprawl and urban sprinkling models, which are studied both for the state of the art [14–16] and for implementing techniques, tools, and simulations for reversing the tendence [17–19].

Some studies have focused on definitions of peri-urban, from the studies on the 'Diffuse city' which aimed at describing the tendence of a dispersive structure in urban space derived by dynamics and social-economic processes [20]. In the late 1990s in Europe, such construction trends have generated many local parceling out, that were characterized by single constructed interventions scattered around the territory including both historical tissue and new settlements. Such dispersal structure of the city has been described in various ways which emphasize the morphology changes, such as 'Metropolitan archipelago' [21] and enclaves [22].

The present work presents a methodology that has been used in the LIFE IMAGINE Umbria project. The aim of the paper is to deal with urban areas' classification starting from the specific necessity to recognize and schematize the complex reality with the aim of approaching the issue of environmental continuity.

The paper is organized in five paragraphs. Paragraph 2 explains the methodology exploring used data and the classification process. Paragraph 3 focuses the obtained results which consist in 17 recurrent configurations of urban and peri-urban areas. Then, paragraph 4 explores some main limits and considerations derived from the study. In conclusion, the author expresses the general overview on the findings of the methodology and the developments to be implemented in future (paragraph 5).

2 Materials and Methods

The paragraph is articulated in two sub-paragraphs. It presents the methodology following the presentation of material and methods and then the process of analysis that leads to the classification of urban and peri-urban configurations (Fig. 1).

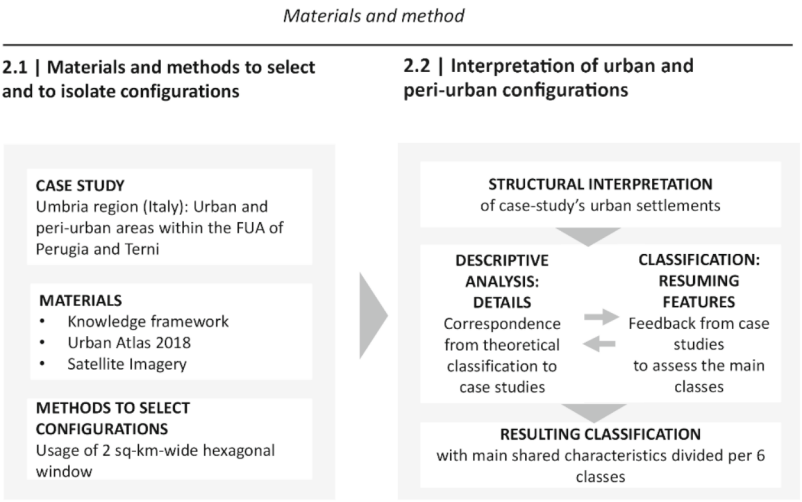


Fig. 1. Flowchart of the methodology. Source: Own elaboration.

2.1 Materials and Methods to Select and to Isolate Configurations

The proposed approach is comparative and qualitative. It is based on a comparative analysis considering the existent literature on the urban gradient and the land cover/ land use data and satellite imagery available for the case study. The land cover and land use information (LULC) are based on the Copernicus Land Monitoring Service (CLMS) [23]. Specifically, the focus is on the section of pan-European component (CORINE Land Cover) and the local component (Urban Atlas) composed of main Functional Urban Areas (FUA) [24]. In Umbria region, the areas that present such data are the FUAs of Perugia and Terni (Fig. 2). Then, satellite images are used for the high-resolution and wide coverage of data for the detailed analysis of urban settlements.

For giving substance to the comparison among different settlement then is introduced a figure of reference in order to frame the selected configurations with one dimension and shape. The hexagonal shape is considered suitable as it refers to the hexagonal cell used in urban grids. The use of hexagonal shape has advantages derived both from the equal distance between the centre and each edge, and the relationship among grids' cells. (Fig. 3) [25, 26]. As instance, spatial accessibility analyses use these characteristics for having a better representation of connectivity and neighborhood relations [27, 28]. Such properties are considered useful for developments of the research [29].

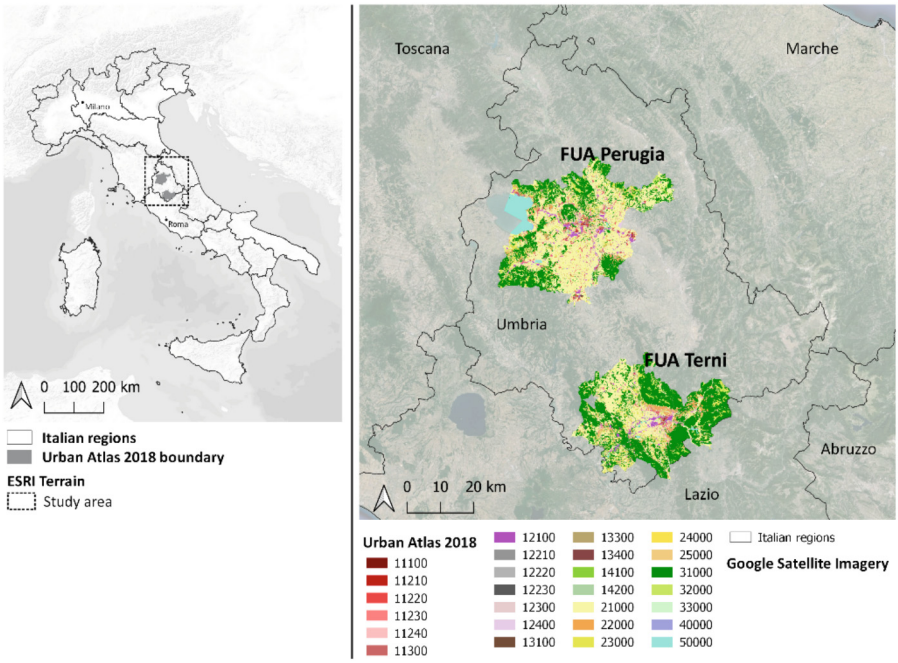


Fig. 2. Case study area. General framework of Italy (on the left side) and Umbria region with the two selected FUAs considered in the present work (on the right side). Source: Own elaboration. Data from Google Map, Copernicus data.

The use of such shape-window is here released from any grid system. For the present analysis, the use of a free shape is proposed as solution for identifying recurrent areas in every position they are, differently from what would have happened with the use of grids that are randomly located [16]. As one hand lens, the hexagonal window is "moved" on the case study area, and it is arbitrarily stopped where it frames one recurrent configuration.

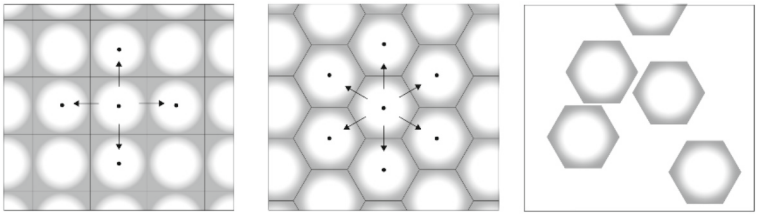


Fig. 3. General properties of grids compared to the singular window that is used for the present methodology. Source: Own elaboration.

Window's dimension then must be settled to frame significant portions of the urban and peri-urban configurations. To this extent, the window's dimension is chosen as the

doubled data of the average CLC urbanized areas in the case study. The layer of artificial surfaces (classes from 1.1 to 1.4) is considered for fitting the average dimension of one urbanized area and its surrounding. According to this data, the medium value of single polygons of artificial surfaces as mapped in the CLC is about 100 ha (86,5 ha). Considering the double of the data, the dimension results equal to 200 ha/2 km^2.

As further tool, a visual isolation of the area is elaborated using six adjacent empty cells around the window. This is functional to isolate only the analyzed area from external elements (such as other parts of the settlement, infrastructures, or other settlements) (Fig. 4).

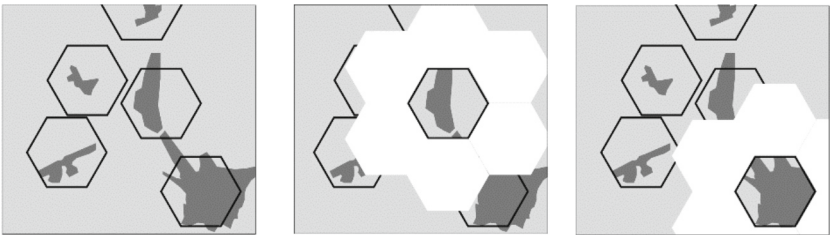


Fig. 4. Windows and isolation of the configuration. Source: Own elaboration.

2.2 Interpretation of Urban and Peri-Urban Configurations

Given the framework of tools, critical approach is fundamental for distinguishing shapes, level of aggregation and characteristics of urban settlements. How to classify the gradient with its unclear scattered borders, variations, and irregularities [11]? Structural and functional interpretation are possible analyses [30]. However, such work implicates the reduction of complex system (the reality) in different possibilities of settlements (the model) which can be associated to the real gradient (Fig. 5).

The proposed structural interpretation consists in the match between identification of the urban structure and interpretation of quality of the urban environment. The process is based both on the specificities of the case study and on the knowledge framework.

The analysis is carried out through two steps. Firstly, identification of real settlements approaches the local specificities of the case study. Secondly, the definition of the main classes is aimed at giving coherence in one homogeneous classification. The theoretical classification is done in mutual progression with the descriptive analysis of real settlements (Fig. 5).

The descriptive analysis proceeds to frame the recurrent settlements due to the use of the hexagonal window. Then, the descriptive analysis acquires information related to the context, the morphological features that affect distribution of settlements. This aspect includes identification and description of natural elements as mountains, rivers, lakes etc. When urbanized areas are present, the level of occupation of the soil is studied through the sealing soil data (Urban Atlas). Such information is integrated with evaluation of typology of buildings, grades of compact tissues as well as interstitial natural areas as readable in satellite images.

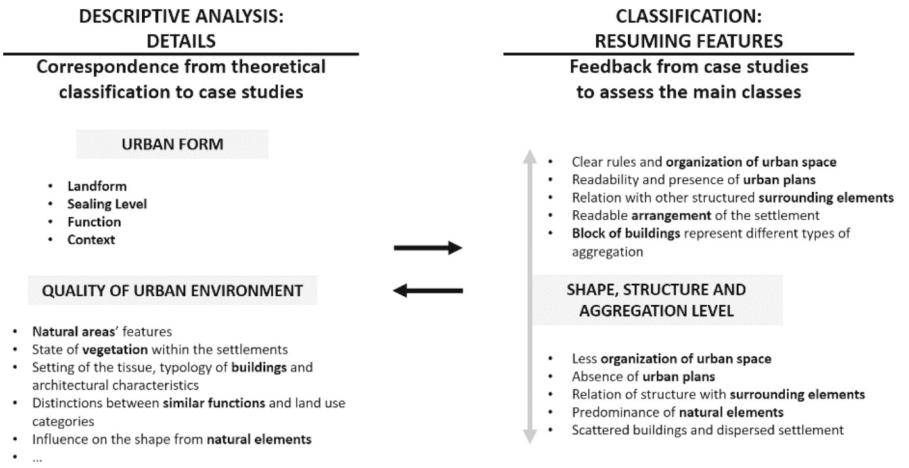


Fig. 5. The process of classification. Source: Own elaboration.

Then, function and uses are useful for understanding specific characteristics of the settlement. Even though the window is ideally isolated in its analysis, the context can be derived from elements in the window that give information on the matrix of reference. The study of the road network is then considered for focusing on the presence and the types of streets (highway, main road, high-speed road, provincial and minor streets) inside the window and the road network that draws the settlement.

There is also the observation of the state of vegetation within the settlements. Vegetation can be mature and full-grown, then it can indicate the co-presence of enduring settlements. On the contrary, youth plants can indicate a recent settlement. At the same time, same species and organizations of the plants can indicate a plan behind the construction. The setting of the tissue, the typology of buildings and architectural characteristics are indicative of properties of settlements. Same typology and same building material suggests a structured unitary plan. On the contrary, great diversity among structures and open spaces' design suggest autonomy in the building process. Extreme diversity with a non-structured design of the streets can indicate spontaneous development of the settlement [31].

Secondly, the classification follows a gradient of main structures and aggregation features. Shape and structure are the primary features in considering the artificial area as it appears at the chosen scale. The classification then moves from the most compact structures (aggregated); to the recognizable aggregations along a main direction (linear); to the undefinable prevalent direction and the general dispersion of the artificial elements (spread).

Six main models then are classified from the most compact and aggregated tissue to the absence of buildings and urban shapes (Fig. 6).

1. Aggregated, compact and dense configuration generally represents portion of the urban area. It is comprehensive of historical centre or in proximity of that. This model has readable, structured, and consolidated urban plan. Tissue can be intricate,

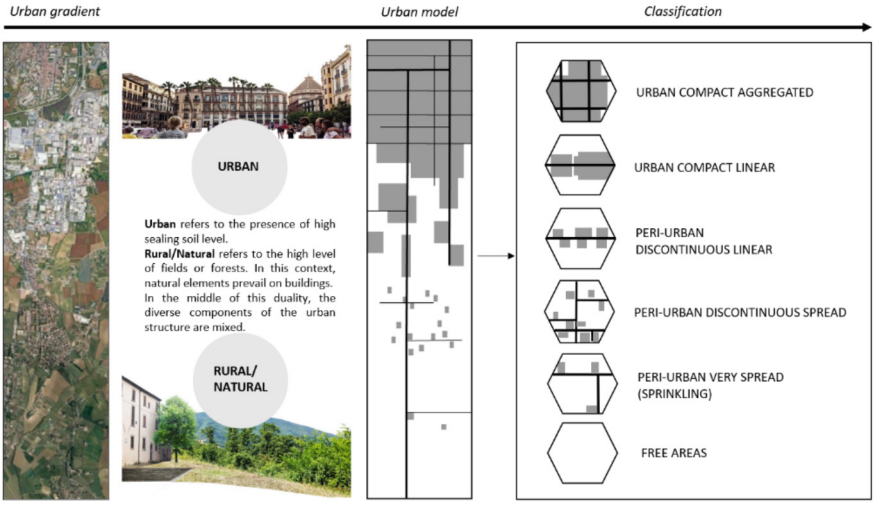


Fig. 6. From the urban and rural extremes to a scheme of the urban gradient. Source: Own elaboration. Data from Google Earth, Copernicus data.

reticular, radio centric or composite. According to the urban zoning, these settlements are included in the A, B, C D and F zones (DM 1444/68).

2. Linear, compact, and dense configuration. Settlement is aggregated along a main path. It can be a provincial or regional road, or a high-speed road. Functions are mixed, often industrial, or commercial units, but also residential areas. Blocks can be sparse or interrupted by empty spaces. These spaces can be marginal or residual areas. According to the urban zoning, these settlements are included in the B, C D and F zones.
3. Linear and discontinuous configuration. Settlement is aggregated along a main path and tissue appears discontinuous. The main path can be a provincial or regional road, a high-speed road or inferior level that connects residential areas. Density varies and structure is porous. Blocks can be organized in wide distances, or they can follow a reticular structure in which empty and residual spaces are present. Also, fragmented parts of farms can be included in the structure. According to the urban zoning, these settlements are included in the B, C, D, and F zones. The main difference with the linear, compact, and dense is the residual space between various settlements. Empty spaces in this scheme weigh as much as sealed areas.
4. Spread and discontinuous tissue. Settlement is discontinuous and scattered with variable density. There is no one path of reference, but some main infrastructures can be present. Blocks can be organized in wide distances, or they can follow a reticular structure, in which empty and residual spaces are present. Also, fragmented parts of farms can be included in the structure. According to the urban zoning, these settlements are included in the B, C, D, and F zones.
5. Very spread tissue in rural context. Settlement is discontinuous and scattered with very low density. In this model rural context is dominant, whereas buildings are spots which follow streets that connect residential areas. Generally, it is located outside and

away from urban centre. Generally, buildings and sealed areas are distant from the main infrastructures. If present, small or medium aggregations form shapes that are not related to the main roads. According to the urban zoning, these settlements are included in the C, D, and E zones.

6. Free areas in rural context. The dominant element is a natural area, such as fields, woods, orchards. Buildings are excluded from this pattern. The class about free areas is a category deprived from artificial land. According to the urban zoning, these settlements are included in the E zones.

3 Results

As a result, the classification matches with 17 windows on the study area. Windows are 9 for FUA of Perugia and 8 for FUA of Terni. The results are divided into 5 recurrent configurations of aggregated compact and dense tissue; 2 Linear, compact, and dense tissues; 2 Linear discontinuous tissues; 3 Spread and discontinuous tissues; 3 Very spread tissue, and 2 configurations of Free areas.

As already prefigured, the development of peri-urban areas follows the proximity of the urban centres [32]. The results highlight that available advantageous morphology (as

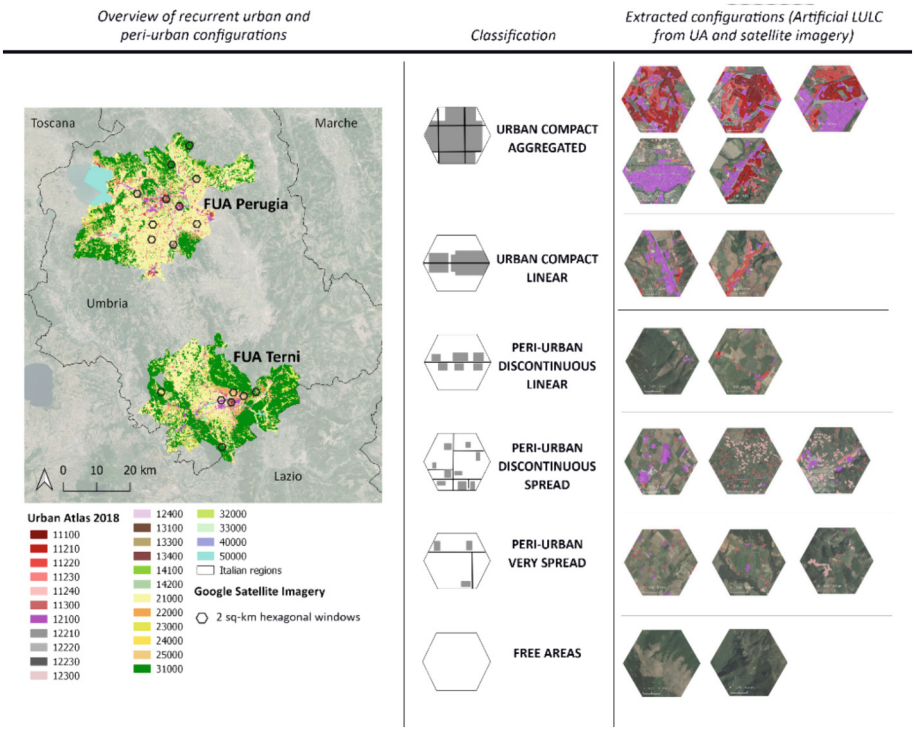


Fig. 7. Results of window classification within the Urban Atlas map and the 17 recurrent configurations selected from the case study. Source: Own elaboration. Data from Google Map, Copernicus data.

agricultural lands) in continuity to the urban core facilitates the presence of heterogeneous peri-urban configurations. Then wider is the rural matrix around the urban centre (as the case of FUA of Perugia), more the urban dispersion may spread in various shapes (from linear to diverse level of dispersion). On the contrary, a mountain environment might limit expansion prospects since the soil available for expansion is limited (as it is partially in the case of FUA of Terni) (Fig. 7) [11].

The considerations done for each configuration converged in single insights realized as worksheets. Each worksheet summarizes the main characteristics derived from the study (Fig. 8). A worksheet corresponds to one configuration, and it indicates the place name, the general overview in the CLC framework and the hexagonal window showing the UA 2018 Land use and land cover information (LULC) with the Google satellite imagery. The illustrating worksheets are comprehensive of satellite imagery at various scales, sketches of the main shapes of the settlement and the main road network. The sum of worksheets give shape to a collection of qualitative detailed presentations of each configuration. Such research products are part of the A2 action's report "Preliminary analysis of urban and peri-urban areas".

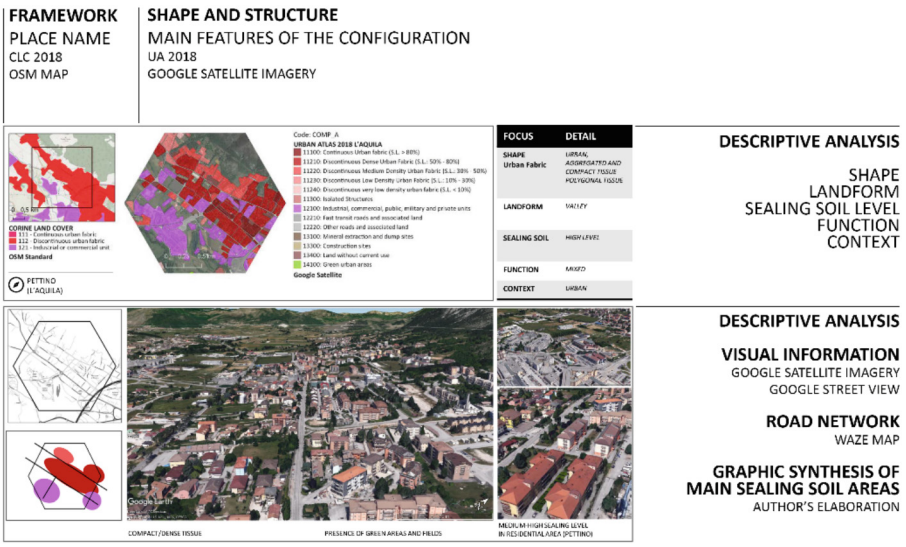


Fig. 8. Summary worksheet that resumes the qualitative investigation on a singular window. Source: Own elaboration. Data from Google Earth Image Landstat/Copernicus, Copernicus data.

4 Discussion

In the present work, the FUA set the perimeter of the analysis, including areas around the urban core and excluding all the areas outside the boarder. Such limit imposes to exclude more peripheral configurations, which would be interested to compare if the Urban Atlas data covered larger areas around the urban cores. Indeed, it seems easier

to find out urban and peri-urban configurations which are denser, whereas uninhabited and building-free areas are present in less quantity. Although the focus of the research is related to urban growth and environmental continuity, other interesting comparisons might regard the welfare-related issues like social services and connections [33].

Then, some general considerations have arisen from the results (Fig. 7).

1. Aggregated, compact and dense tissue are generally part of the historical centres or productive plants. The blocks and the high sealing soil cover almost all the area. The shape might be related to one central point of interest or aggregation.
2. Urban linear, compact and dense tissues are mostly linear productive plants aligned along a main road. Linearization is a typical way of proceeding in urbanization development, and it is highly functional for productive plants and logistic centres. The proximity and the direct access to the main road, services, and resources' infrastructures might be related to economic convenience.
3. Peri-urban Linear discontinuous tissues have varied properties. Settlements are mainly residential areas of small towns. Generally, the low high space between building and the low density is given by a mountain area, impervious or inaccessible areas.
4. Peri-urban spread and discontinuous tissue present mainly scattered configurations which highly depend on the terrain morphology. The configurations are highly variable.
5. Peri-urban very spread tissue is mainly in rural valley context. The vocation of this area is mainly agricultural, and the few scattered buildings are main residential units.
6. Free areas have been found at the borders of the FUA and they mainly share mountainous morphology. The type of involved non-artificial soil is variable (from fields to woods).

In the present work, calibration among different classes has been one of the main discretional choices. For the specific case study, three main choices in terms of distinctions have been done during the classification of the main configurations.

Linear, compact, and dense configuration is one of the most critical categories to define for the case study. The definition of this model dealt with the difficulty in distinguishing different types of compact tissues. A first recognition has included also some aggregated compact tissues because of their main axial development. This has been the case of extended industrial sites that develop on one or two main infrastructures. Then a calibration is made in terms of aggregation. Compact tissues that are more aggregated than linear have been labelled as aggregated compact tissue. On the contrary, compact tissues with strong axial development have remained in the compact linear class (Fig. 9).

Spread and discontinuous configuration is uneasy to identify, and it presents many specificities and variations in each context. Previously, a rough classification of spread/discontinuous tissue included the typical sprawl configuration or mixed discontinuous tissues that might be associated with the sprawl model. However, sprawl model has a defined recognizable configuration which should be considered apart from the general discontinuous tissue (Fig. 9) [14]. Since the typology is not common in the case study, the specific case has been excluded from the classification.

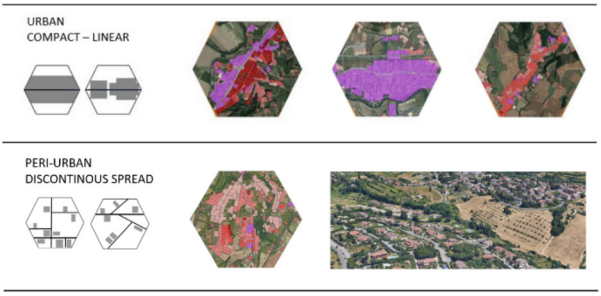


Fig. 9. First classifications of linear compact and dense configurations and example of one (non-recurrent) configuration representative of the sprawl model. Source: Own elaboration. Data from Google Earth Image Landstat/Copernicus, Copernicus data.

Moreover, evident variations in discontinuous tissues have led to the necessity of calibrating two different levels of discontinuous classes. Among the classes, the two discontinuous are the most similar ones. As highlighted in introduction, the discontinuous tissues can vary consistently, and such variations are object of several studies on urban growth models [15].

Furthermore, the selection has been guided by the necessity of coherence inside the classes. Coherence among configurations of the same class is a prerequisite both for the classification itself and for further studies. In fact, the choice of a defined shape (the hexagon) can be also functional to other applications. Phenomena as urban dispersion is studied with methodologies that uses grids. Research have already demonstrated that there is a difference between a grid-base results and an administrative borders' ones [16]. The hexagonal window is part of development lines of research in relation to process of automatic recognition of urban configurations that might cover all the case study area [26]. In the present work, the descriptive and qualitative analysis is a process of reasoning that is not replaceable with software or automatic techniques. However, it has already been used for experimental approach aimed at automating the recognition of recurrent urban and peri-urban configurations given the illustrated classification. In fact, the classification can serve as a dataset, for which the ratio has been defined due to the study of the territory and it can be supportive of semi-automatic machine learning models. Given the distinction in classes, the semi-automatic model can automatically implement the classification for a selected area. The implementation produces a combined methodology between descriptive and computational approaches which has given promising results [29].

5 Conclusions

The theme of peri-urbanization is wide, and it is supposed to be a pivotal question in urban studies for a long time yet. This work deals with the opportunity to improve sectorial classifications used for distinguishing urban and peri-urban areas.

Even though urban elements are related to urban dynamics, the classification has been done considering the readable elements in the current situation. Then, the differences

between the 6 configurations are defined by comparisons among the cases present in the case study and the knowledge framework. Moreover, the methodology may represent a step towards the use of a qualitative to a more computational approach due to the use of the selected window. The role of the author in the present work is relevant for developing the classification. However, the same approach on different case studies might bring to variations to the classification. Although the produced classification is considered suitable for recognize most urban settlements in Italy, next steps of the research include the study of new FUAs in Italy and Europe.

Also, the worth stands in the practical application that the study had within the LIFE IMAGINE Umbria project. The presented approach has in the project its real field of application, as the worksheets have already converged in the implemented project's methodology and in the guidelines of the Action A2 [8].

Among the goals of the project, modelling the urban growth is fundamental both for analyze the present state and for forecasting future scenarios in relation with the protection of Natura 2000 Network. The classification then is a crucial node for defining guidelines for restoring environmental continuity because it permits to give differential responses to different areas. In fact, study of configurations can serve for targeted interventions to implement, in line with the assumption that urban and peri-urban configurations may need different approaches to the urban project [34]. As instance, de-sealing methods can be the prevalent goal for a compact dense area. Conversely, reconfiguration should be the best solution for spread tissues. Peri-urban areas may be also involved in reconfiguration of the territory for including green infrastructure and protection of existent interstitial open spaces [35]. In this sense the classification of urban and peri-urban configurations is a tool for studying targeted projects. At the design level, each configuration can fit a series of interventions and projects then can give specific solutions to configuration-related issues. In perspective, sustainability and performance of settlements should be evaluated through the classification of configurations. Ultimately, configurations might be usable for defining planning strategies as implementation of regeneration and resilience policies [36].

Acknowledgments. The analysis is developed within the Integrated Project LIFE IMAGINE UMBRIA (LIFE19 IPE/IT/000015 – Integrated MAnagement and Grant Investments for the 2000 Network in Umbria).

References

1. UN-Habitat: World Cities Report 2020. The Value of Sustainable Urbanization (2020)
2. Serra, P., Vera, A., Tulla, A.F., Salvati, L.: Beyond urban-rural dichotomy: exploring socioeconomic and land-use processes of change in Spain (1991–2011). Appl. Geogr. **55**, 71–81 (2014). https://doi.org/10.1016/j.apgeog.2014.09.005
3. Sargolini, M.: Urban Landscapes: Environmental Networks and Quality of Life. Springer, Heidelberg (2013). https://doi.org/10.1007/978-88-470-2880-7/COVER
4. Carta, M., Gisotti, M.R., Lucchesi, F.: Settlements and urban morphological quality in landscape planning. Analytical models and regulating tools in the landscape plan of Regione Toscana. Sustainability (Switzerland). **14** (2022). https://doi.org/10.3390/su14031851

5. Romano, B.: Rete ecologica del Veneto. Analisi delle interferenze ambientali e linee di pianificazione. Rapporto finale (2006)
6. LIFE IMAGINE. https://www.lifeimagine.eu/. Accessed 12 Apr 2023
7. European Commission: The Habitats Directive. https://environment.ec.europa.eu/topics/nature-and-biodiversity/habitats-directive_en. Accessed 03 Mar 2023
8. Di Dato, C., Pierantoni, I., Fiorini, L., Marucci, A., Sargolini, M.: Characterization of urban and peri-urban areas in Umbria region to identify their possible role in the conservation of Natura 2000 network. In: Marucci, A., Zullo, F., Fiorini, L., Saganeiti, L. (eds.) INPUT 2023. LNCE, vol. 463, pp. 659–668. Springer, Cham (2024). https://doi.org/10.1007/978-3-031-54096-7_57
9. Ravetz, J., Fertner, C., Nielsen, T.S.: The dynamics of peri-urbanization. In: Nilsson, K., Pauleit, S., Bell, S., Aalbers, C., Sick Nielsen, T. (eds.) Peri-Urban Futures: Scenarios and Models for Land use Change in Europe, pp. 13–44. Springer, Heidelberg (2013). https://doi.org/10.1007/978-3-642-30529-0_2/COVER
10. Cattivelli, V.: Delimiting rural areas: evidence from the application of different methods elaborated by Italian scholars. Land **11**, 1674 (2022). https://doi.org/10.3390/LAND11101674
11. Sahana, M., Ravetz, J., Patel, P.P., Dadashpoor, H., Follmann, A.: Where is the peri-urban? A systematic review of peri-urban research and approaches for its identification and demarcation worldwide. Remote Sens. **15**, 1316 (2023). https://doi.org/10.3390/RS15051316
12. ISTAT: FORME, LIVELLI E DINAMICHE DELL'URBANIZZAZIONE IN ITALIA (2017)
13. Piorr, A., Ravetz, J., Tosics, I.: PERI-URBANISATION IN EUROPE Towards European Policies to Sustain Urban-Rural Futures SyNThESIS REPORT (2011)
14. Egidi, G., Cividino, S., Vinci, S., Sateriano, A., Salvia, R.: Towards local forms of sprawl: a brief reflection on mediterranean urbanization. Sustainability **12**, 582 (2020). https://doi.org/10.3390/SU12020582
15. Romano, B., Zullo, F., Fiorini, L., Ciabò, S., Marucci, A.: Sprinkling: an approach to describe urbanization dynamics in Italy. Sustainability (Switzerland). **9** (2017). https://doi.org/10.3390/su9010097
16. Saganeiti, L., Favale, A., Pilogallo, A., Scorza, F., Murgante, B.: Assessing urban fragmentation at regional scale using sprinkling indexes. Sustainability (Switzerland). **10** (2018). https://doi.org/10.3390/su10093274
17. Marucci, A., Fiorini, L., Zullo, F., Di Dato, C., Tomei, V., Romano, B.: Vision and project to retrofit the "urban dust" scenario: simulation in the region of Umbria, Central Italy. J. Urban Plan. Dev. **147** (2021). https://doi.org/10.1061/(asce)up.1943-5444.0000722
18. Romano, B., Zullo, F., Marucci, A., Fiorini, L.: Vintage urban planning in Italy: land management with the tools of the mid-twentieth century. Sustainability (Switzerland). **10** (2018). https://doi.org/10.3390/su10114125
19. Romano, B., Fiorini, L., Zullo, F., Marucci, A.: Urban growth control DSS techniques for de-sprinkling process in Italy. Sustainability (Switzerland). **9** (2017). https://doi.org/10.3390/su9101852
20. Indovina, F.: La città diffusa: cos'è e come si governa. Daest IUAV, Venezia (1990)
21. Indovina, F., Doria, L., Fregolent, L., Savino, M.: Dalla città diffusa all'arcipelago metropolitano. Franco Angeli (2009)
22. Petti, A.: Arcipelaghi e enclave. Architettura dell'ordinamento spaziale contemporaneo. Bruno Mondadori (2007)
23. Copernicus Land Monitoring Service: CORINE Land Cover. https://land.copernicus.eu/pan-european/corine-land-cover. Accessed 14 Apr 2023
24. Copernicus Land Monitoring Service: Urban Atlas. https://land.copernicus.eu/local/urban-atlas. Accessed 14 Apr 2023

25. Burdziej, J.: Using hexagonal grids and network analysis for spatial accessibility assessment in urban environments - a case study of public amenities in Toruń. Miscellanea Geographica. **23**, 99–110 (2019). https://doi.org/10.2478/MGRSD-2018-0037
26. Fiorini, L., Falasca, F., Marucci, A., Saganeiti, L.: Discretization of the urban and non-urban shape: unsupervised machine learning techniques for territorial planning. Appl. Sci. (Switzerland) **12** (2022). https://doi.org/10.3390/app122010439
27. Levine, A.S., Feinholz, C.L.: Participatory GIS to inform coral reef ecosystem management: mapping human coastal and ocean uses in Hawaii. Appl. Geogr. **59**, 60–69 (2015). https://doi.org/10.1016/J.APGEOG.2014.12.004
28. Birch, C.P.D., Oom, S.P., Beecham, J.A.: Rectangular and hexagonal grids used for observation, experiment and simulation in ecology. Ecol. Modell. **206**, 347–359 (2007). https://doi.org/10.1016/J.ECOLMODEL.2007.03.041
29. Di Dato, C., Falasca, F., Marucci, A.: Machine learning techniques for the semiautomated recognition of urban and peri-urban configurations. In: Gervasi, O., et al. (eds.) ICCSA 2023. LNCS, vol. 14109, pp. 16–29. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-37120-2_2
30. Gottero, E., Cassatella, C., Larcher, F.: Planning peri-urban open spaces: methods and tools for interpretation and classification. Land (Basel). **10** (2021). https://doi.org/10.3390/land10080802
31. Romano, B., Zullo, F., Fiorini, L., Marucci, A.: Illegal building in Italy: too complex a problem for national land policy? Cities **112**, 103159 (2021). https://doi.org/10.1016/J.CITIES.2021.103159
32. European Environment Agency: Land take and land degradation in functional urban areas (2021)
33. Di Dato, C., Marucci, A.: Fragile territories around cities: analysis on small municipalities within functional urban areas. In: Gervasi, O., Murgante, B., Misra, S., Rocha, A.M.A.C., Garau, C. (eds.) ICCSA 2022. LNCS, vol. 13378, pp. 427–438. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-10562-3_30
34. Cutini, V.: La Forma del disordine. Tecniche di analisi e progetto urbano ai tempi dello sprawl. Materiali di architettura e di urbanistica 2016 (2016)
35. European Environment Agency: Green infrastructure and territorial cohesion. The concept of green infrastructure and its integrationinto policies using monitoring systems (2011)
36. OECD: Italy's National Action Plan for Policy Coherence for Sustainable Development. OECD (2022). https://doi.org/10.1787/54226722-EN

Renewables Energy Communities to Restore the City/Country Relationship: The Case of San Severo in the Apulia Region (Italy)

Michele Vomero[1(✉)], Antonio Leone[2], and Maria Nicolina Ripa[1]

[1] Università degli Studi della Tuscia, Via S.M. in Gradi n.4, 01100 Viterbo, Italy
michele.vomero@unitus.it
[2] Università del Salento, Piazza Tancredi, 7, 73100 Lecce, Italy

Abstract. The interrelation between the processes of urbanization and global issues including climate change, energy shortage and food crisis have an influence on the interaction between the city and rural regions. Given the complexity of such processes, which are primarily the result of human activity, it is evident that innovative policy guidelines, as well as instruments, are needed to effectively address these issues within a multitude of territorial contexts.

To revitalize the "peri-urban agricultural" territory as a heterogeneous and dynamic space to be shared between citizens and farmers, with the aim of producing not only food but also energy, it is necessary to investigate potential urban-rural synergies for the adoption of new models according to a holistic and sustainable perspective. These models, also known as energy communities, share energy generated locally from renewable sources.

This paper examines EU, national and local instruments or regulatory initiatives in support of energy production from renewable sources, particularly renewable energy communities (RECs), with specific reference to the European and Italian contexts.

In this regard, an ecosystemic management model for a peri-urban area is proposed, using the Municipality of San Severo in the Apulia Region (Italy) as the study area. This model connects the spaces surrounding the cities to the rural territory by facilitating the diffusion of food models aimed at bringing local consumption and agriculture closer together (urban gardens). It also makes use of eco-sustainable energy systems, such as agro-photovoltaic, aiming at a proximity integration between these two dimensions for a new "city-country pact."

Keywords: peri-urban agriculture · renewable energy communities · agro-photovoltaic system

1 Introduction

Urbanisation in Europe is an evolving phenomenon, both in terms of urban sprawl and population growth, due to the rapid development of urban areas, industries, particularly the tertiary sector, as well as communication and transport infrastructures. It is generally

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 32–49, 2024.
https://doi.org/10.1007/978-3-031-65238-7_3

recognized that cities will soon be the primary source of environmental issues, especially in terms of climate change and energy crisis, as a result of the population's natural tendency to concentrate in larger areas and the ensuing acceleration of country's urbanization [1]. Italy has experienced a significant growth in urbanization, with over 900 km^2 added to its urban area and about 2,500 km^2 added to its suburban area between 2006 and 2022 [2]. The degree of urbanization on a regional scale has also affected Apulia, where more than 500 hectares of land have seen a rise in the density of artificial cover and land consumption, shifting to urban (+13.3%) and suburban (+15.7%) regions. This provides a measure of an urban continuity and a decline in rural areas. The line between what is rural and urban, however, has gradually changed into a novel setting that is neither totally city nor country because urban expansion takes on diversified patterns [3]. These suburbs are located on the fringes of non-urban (rural) territory. They have grown to engulf the land, taking up space that could have been used for agriculture. As a result, there are now more marginal and abandoned agricultural areas, with biodiversity being lost, land and soil degrading and consumption, and environment and landscape changing [4]. They especially exhibit unpredictable and frequently highly de-qualified in-situ forms due to the extremely complex dynamics that developed them; these places are now known as "peri-urban zones" [5] or final periphery. A loss of connection among these spaces has often happened within this framework of physical dissolution of the interaction between the city and the agricultural land. The goals of the EU's energy and climate policy, the Territorial Agenda 2030 [6], the European Green Deal [7], and the 17 Sustainable Development Goals [8] are all in line with this crucial and increased interaction among rural and urban regions. Strong evidence supporting this can also be found in the scientific reports [10] of international bodies on the risks of climate change and the environmental agreements outlined in the framework of Climate Conventions [9]. These sources are relevant in steering the processes of urban quality regeneration, but they also need to be integrated and associated with environmental, urban and territorial planning, design strategies and procedures using self-sustainable local development models, and an integrated extra-strategic approach.

The current state of our cities has been characterized by a high demand for resources: the primary daily inputs from surrounding areas are water, electricity, raw materials and healthy food. The management of the connection between the two main urban subsystems of town and country, according to multi-sectoral standards, seems the ideal starting point to test out policies supporting equitable, sustainable and well-balanced rural and urban growth [11]. Through the implementation of modern agro-photovoltaic technologies on agricultural land, local communities can choose to produce clean, self-produced and sharable energy [12], consequently leveraging their role and stimulating the creation of new economic activities that can, on the one hand, conserve and recover peri-urban agricultural areas [13] by preventing the unrestrained growth of the city, and, on the other hand, identify possible alternatives to the current model of energy resource management. The concept of 'agro-photovoltaic systems' is widely used by the scientific community [14] and also by many government agencies [15] and public administrations [16].

In the light of the above, the goal of this paper is to identify the current EU, national and regional regulatory acts that are relevant to support renewable energy sources, while also taking into account the provisions on the support of the agricultural sector. This is

carried out by starting with the concept of the "multifunctionality" [17] of the primary sector, which can be defined as the production of positive externalities that have both direct and indirect effects on the territory to which they belong, such as renewable energies, and which improve the health of urban ecosystems and their inhabitants.

Based on a local scale analysis, the Municipality of San Severo (Foggia) in the Apulia Region will act as the study area for confirming the importance as well as the feasibility of urban sustainability implementation, or its possible declinations, in order to include "agro-urban parks" in the Apulian territory.

2 The Regulatory Framework

The regulatory framework study must include a comprehensive assessment of the impact that legislative and programmatic actions might have on the relative weights of the many factors influencing the region. Consequently, taking into consideration the existing regulations applying to regional and municipal spatial planning/landscape instruments, the content of recent major EU and national regulatory sources addressing the issue of renewable energy sources and supporting the agricultural sector will be examined.

2.1 Multifunctionality, Climate and Energy in the Common Agricultural Policy

In order to ensure that farmers have access to new sources of income and community-beneficial services, the EU's Common Agricultural Policy (PAC) emphasizes the diversification of the agricultural sector's economy. This approach not only produces agricultural goods but also public goods, such as improved environmental quality and more appealing rural areas [18].

A multifunctional view of agriculture is prevailing, with a focus on the preservation of ecosystems provided by agricultural practices and the need to support interventions in equilibrium with other territorial, energy, and climate policies [19], while at the same time respecting the complexity of agrarian landscapes. With full recognition of the concept of multifunctionality in rural development pro-grams, the PAC has embraced this need and identified environment conservation and landscape enhancement among the main objectives to be achieved, through primary sector activities geared towards multifunctionality, as a paradigm for sustainable rural development. The European Landscape Convention [20] recognized landscape enhancement as one of the most important challenges that national and community policies must respond to.

A role for agriculture is explicitly assigned in the most recent version of EU programming (2023–2027) by the PAC [21], with special emphasis on the targets and commitments made by the EU both internationally and within the framework of the 2050 climate and energy policy. This role extends beyond the productive function of agriculture to include support for the regions and the environment.

Italy has submitted its own version of the National Strategic Plan [22] within the framework of the Common Agricultural Policy to the European Commission, ensuring continuity with EU programming and, consequently, with the provisions of the 2023–2027 PAC, anticipating the implementation of the common objectives of environmental, economic and social sustainability in its various declinations. The Plan consolidates the

necessary financial resources and actions to improve synergies between the agricultural system and other territorial identities into a single programming document for the first time.

Table 1. Rural Development Programmes

INTERVENTION	TYPES OF INVESTMENTS
SRD01	- Productive agricultural investments for the environment, climate and animal welfare - Investments in agricultural companies for diversification into non-agricultural activities
SRD02	- Investments for climate change mitigation (reduction of emissions and/or increase of carbon sequestration capacity in the soil, construction of plants to produce energy from renewable source)
SRD03	- Investments for the maintenance of greenery and the territory also through the creation of environmental services carried out by the agricultural company for the care of non-agricultural spaces - Investments in support of social agriculture; educational/didactic activities; transformation of agricultural products and their processing and marketing in company sales points
SRD04	- Non-productive investments aimed at halting and reversing biodiversity loss and preserving the rural landscape
SRD07	- Investments aimed at integrated planning and integrated territorial planning methods, in compliancy with the Plan
SRD08	- Investments in infrastructures with environmental purposes: energy production (electrical and/or thermal) from renewable sources for collective use (energy communities)
SRD09	- Investments in favor of compromised and critical areas also in urban-rural transition spaces
SRD13	- Investments for the installation of electrical and/or thermal energy production systems using renewable sources, limited to company self-consumption, or for the recovery of heat produced by production plants
SRG06 - LEADER	- Investments for the implementation of the interventions planned in the integrated, multi-sectorial and innovative Local Development Strategies centered on the following thematic areas: 1. Ecosystem services, biodiversity, natural resources and landscape; 2. Local food systems, districts, agricultural and agri-food supply chains; 3. Services, goods, collective and inclusive spaces; 4. Energy, bioeconomic and circular economy communities; 5. Local socio-cultural and tourist-recreational supply systems

In order to achieve this, it is important to emphasize the solid support that the strategically based Rural Development Programmes (Table 1) can provide for policies of this kind through the significant European structural funds made available, in addition to other essential interventions offered by the National Recovery and Resilience Plan (see Sect. 2.2), which needs to be interpreted as an essential component of the national strategy.

Apulia has recently accepted the Regional Complement for Rural Development (CSR) [23] at regional level. This document outlines the strategic decisions and rural development interventions that will be implemented among the initiatives pro-posed by the National Strategic Plan 2023–2027. The program's goals coincide with national and EU policy objectives and guidelines, giving the rural area a strategic role in promoting greater resilience and providing tangible support for the sector impacted by climate change. This puts the value of local specificities and the socioeconomic fabric of agricultural areas at the center of the sector's regional policy.

2.2 Energy-Climate Challenges and the Current Regulatory Framework

It is increasingly evident that agriculture policy and energy-climate challenges are the core of all initiatives to provide competitive, se-cure and sustainable energy for the Community.

The European Union's renewable energy policy was launched in 1997 with the adoption of the White Paper [24]. The goal is to lower emissions that contribute to climate change and reform the European energy system through new technologies and the active participation of European citizens in both the production and consumption of energy. This will ensure that all consumers can access reasonably priced energy-related goods and services. The European Union mainly relies upon organizations with certain structural and functional qualities to enable proper horizontal subsidiarity in the energy sector. This means that the EU focuses on the abilities of its citizens to steer the EU towards a more sustainable development.

In this scenario, the European Commission started working at a package of policies, known as the "2030 Climate Target Plan" [25], on energy, land use and environment, that would reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. This would enable the continent to become a competitive and sustainable climate-neutral economy by 2050. The general EU policy framework was thoroughly reviewed to analyze the progress made towards reaching these goal values (Table 2).

One of the main goals of the "renewables" (2018/2001/EU) and "electricity market" (2019/944/EU) directives, in accordance with the Paris Agreement objectives, is to increase the number of stakeholders who can help Europe achieve its decarbonization targets by 2050. The two directives offer detailed descriptions for two forms of shared energy, i.e. "self-consumption" and "energy communities" (CERs), as well as a regulatory structure for individual and community involvement at European level. Each Member State of the EU must therefore fulfill its own matching objectives for the EU to reach its targets. Nowadays, the combined provisions of Legislative Decree No. 210/2021 Transposing Directive (EU) 2019/944 on common rules for the internal market in electricity and Legislative Decree No. 199/2021 implementing Directive (EU) 2018/2001

Table 2. Summary of Policies, Plans and Programs of the Energy and Climate Sector

Year	Title	Contents/Objectives
2017	**"Winter package" o "Clean Energy for all Europeans Package"**	Legislative package to equip the EU with the necessary tools to address the global energy transition - the foundations of which were laid in the Paris Climate Agreement. The measures introduced aim to create an Energy Union capable of making energy safe, sustainable, competitive and available to EU consumers at affordable prices, by setting additional energy and climate targets for the period 2021–2030
2019	COM(2019) 640, **"European Green Deal"**	The European Green Deal provides the EU with the plan and roadmap to achieve its climate ambitions and to make Europe's climate-neutral economy and society sustainable by 2050
2020	CCOM(2020) 562, **"2030 Climate target plan"**	The European Commission has started the path to make EU policies on the environment, energy, land use, transport and taxation suitable to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels
2021	COM(2021) 550, **"Fit for 55" Package**	The 'Fit for 55' Package adapts existing climate and energy legislation to the new EU target of a minimum 55% reduction in greenhouse gas emissions (GHG) by 2030, and aims to put the EU firmly on the path to climate neutrality by 2050
2022	COM(2022) 230, **"REPowerEU Plan"**	In response to the difficulties and disruptions in the global energy market caused by the Russian invasion of Ukraine, the European Commission presented the REPower Plan: saving energy, producing clean energy, diversifying energy supplies

have completed the general framework of national provisions about CERs. This regulatory framework will be completed and implemented with a focus on renewable energy communities, adhering to European objectives.

In order to facilitate sharing across various self-consumption configurations, including CERs, Legislative Decree No. 199/2021 reduced the restrictions, to expedite the nation's sustainable growth trajectory. The bill has essential requirements for executing the National Recovery and Resilience Plan (NRP) [26] for renewable energy sources, in alignment with the National Integrated Energy and Climate Plan (PNIEC) [27]. The

PNRR actively encourages the creation of energy communities where the prosumers approach can be advanced. To this end, each territory turns into a producer and consumer of redistributed renewable energy, and Mission 2 'Green Revolution and Ecological Transition' provides ample space for the topics of agro-voltaic development, hydrogen, renewable energy, sustainable networks, mobility and more (Fig. 1).

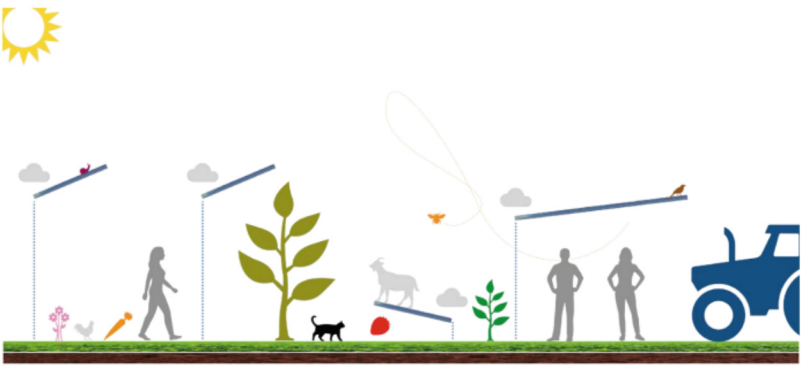


Fig. 1. Source: Ministry of Ecological Transition (MiTE), "Guidelines on Agrovoltaic Systems", June 2022.

The Apulia Region uses the Regional Environmental Energy Plan (PEAR), a strategic planning instrument, to schedule energy interventions within its area. The PEAR was established in 2015 and aims to create a differentiated energy mix by de-creasing the use of coal and increasing the use of renewable sources. It also included the concept of agri-voltaic in its regional legislation [16], permitting 'the installation of photovoltaic systems without allowing the consumption of ecologically productive land and, in particular, without precluding the agri-cultural use of the land itself'.

3 The Agro-Urban Park Between Spatial Government and Energy Policies: A Case Study

3.1 Study Area

This case study examines the Municipality of San Severo in the Region of Apulia (Fig. 2), which might serve as an experimental region encompassing many domains. In fact, the Regional Territorial Landscape Plan (PPTR) of the Apulia Region [28] and the General Urban Plan (PUG) of the Municipality of San Severo [29] present an environmental approach to territorial planning in a systemic vision of its naturalistic, territorial and socio-economic aspects. Agro-urban policies, which combine peri-urban agriculture and urban and suburban regeneration programs, are part of the spatial and landscape planning strategies of both Plans, despite their differing definitions and procedures.

This research aims to enable the analysis of the relationship between the rural and urban areas—referred to as a "green corridor"—which would facilitate the development of a multipurpose peri-urban agriculture model including the production of both food

and energy. This would result in the development of locally generated, renewable energy-based, eco-sustainable (agro-photovoltaic) and energy-sharing systems—also known as energy communities.

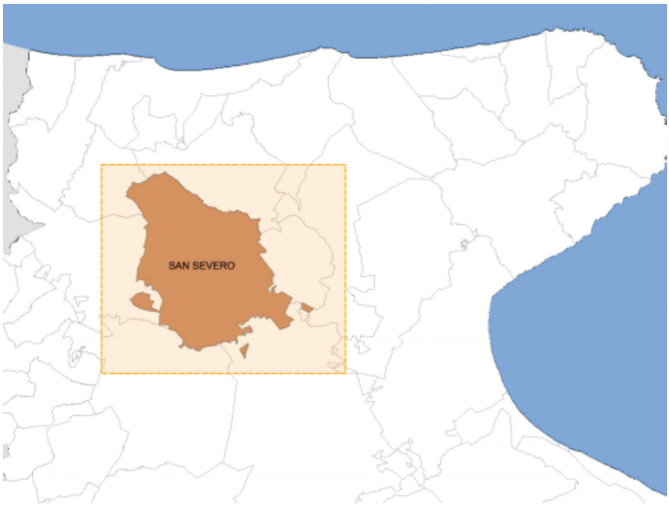


Fig. 2. General Urban Plan (PUG) of the Municipality of San Severo

3.2 Land-Energy Relationship

To understand the complex composition of the peri-urban agricultural space and its social and environmental roles, the Apulia Regional Territorial Landscape Plan (PPTR) focuses on the concept of the peri-urban that views the periphery of the city as project areas from which to restart in order to restore quality in urban settlements, considering rural landscape as a fully cultivable and liveable space.

To address these developments from such a perspective, the Apulia PPTR introduced a strategy and planning component that works by setting goals and recommending public and private actors and actions that can help transform the area. In order to achieve this, the traditional hierarchical regulatory and sequential approach to the planning process is abandoned in favour of continuous cooperation and interaction for the creation and implementation of projects, policies and interactions between public institutions and planning authorities, at local and regional levels, as well as the general public. By responsibly improving the declined landscapes of modern urbanization, such measures would result in a change of geography.

The strategic scenario includes spatial projects for local landscape, general and particular quality targets, and recommendations for the layout and location of renewable energy installations. The Plan takes the patrimonial values of the Apulian landscape and translates them into transformation objectives to counter its degradation trends and build the preconditions for forms of *"self-sustainable local development involving the*

strengthening of productive activities connected to the enhancement of the territory and local cultures" and *"development of local energy self-sufficiency in accordance with the raising of environmental and ecological quality"*.

Regarding the renewable energy component, the Plan focuses its energy-related efforts on maximizing the potential energy mixes unique to the area and developing public-private partnerships (energy community projects) that can effectively address environmental preservation, economic sustainability and regional spillover effects. These factors support the idea of a decentralized energy supply system in accordance with international laws by encouraging to reconsider a city and region with low consumption but strong output potential.

These core goals are reinforced and refined in the complex 'City-Country Pact' of the Apulian PPTR. The 'City-Country Pact' is one of the five territorial initiatives of regional landscape, which collectively embody the Apulian landscape plan's strategic vision (Fig. 3).

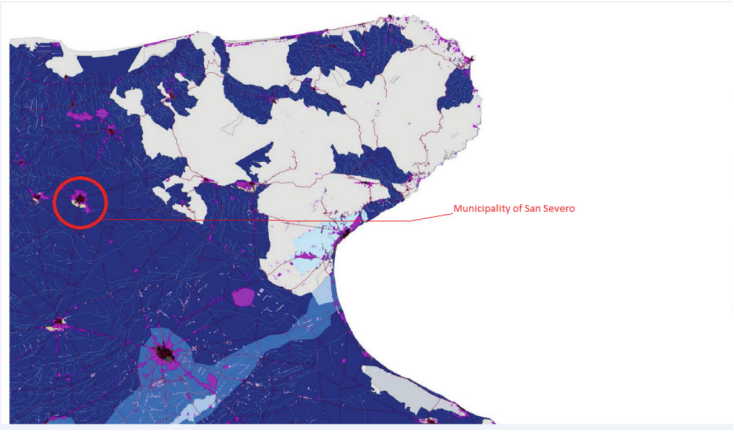


Fig. 3. The city-country pact, PPTR - Apulia Region

The 'City-Country Pact' aims to restore environmental and landscape quality to both territories, starting with the criticalities of modern urbanization and the processes of rural landscape degradation. The urban territory will be improved by clearly defining its boundaries, functions and public spaces, which historically defined it. The rural territory will be improved by reclaiming its unique characteristics and functional qualities, overcoming the double degenerative processes of rural landscape degradation and urbanization. These spaces are given a function in the design scenario that is connected to both enhancing urban quality and the productive component. Under the first point, which introduces the concept of multifunctionality, "agriculture is called upon to perform tasks that include not only producing food of high quality but also protecting hydro-geological systems, improving the quality of the environment and landscape, producing energy, and igniting locally based economic systems (zero-hectare, short production and consumption networks; ecological footprint reduction through the localization and closure of food, waste and energy cycles)."

In this regard, the multipurpose nature of peri-urban agriculture and its services acquire a special significance in the revitalization of suburbs, the enhancement of metropolitan regions' standard of living and the general urbanization process. The second is to enhance Urban quality is enhanced by redeveloping suburban open space that has been designated as "restricted areas" in the plan (peri-urban connection rings, multifunctional agricultural parks and CO2 parks), where standards of territorial and landscape quality can even be defined in relation to the development of renewable energy sources.

The Municipality of San Severo modified its own General Urban Plan (PUG) to comply with the superior regional planning tool in close conjunction and define the development guidelines for its future territorial transformation. The plan comprises programmatic section addressing the implementation of the PPTR's «City-Countryside Pact» and defines the extra-urban system and the areas designated for agricultural activities, to make them "likely to develop and be structured as a multifunctional park".

To achieve this and prevent soil consumption and erosion for the centrifugal urban expansion of non-coherent fabrics in proximity of the compact grid of valuable historical buildings characterising the local context, peri-urban areas have been identified on a municipal scale through the reconstruction of the urban margins with the creation of green belts (Fig. 4).



Fig. 4: Source: PUG Programmatic Part, Implementation of the Strategic Plan, City-Country Pact (PUG Table 3)

Given that the energy topic is becoming more and more important and is starting to heavily weigh on decisions made by territorial authorities, increasingly aiming at multi-sectorial interventions, this planning tool is innovative in comparison to traditional practices of territorial planning and programming, despite needing to be revised in its characterizations and declinations.

3.3 Energy Balance at Municipal Level

From these assumptions, it is essential to take into consideration electricity balance data starting at the supra-municipal level of the Municipality of San Severo to be able to consciously plan any actions to be taken in the territory with a view to energy transition. To this end, summary tables were drawn up, based on official statistical data, on demographic development [30] and electricity consumption in the municipal area [31]:

a) Demographic indicators:

People living in each area, along with their demographic traits and socio-behavioural trends (such as lifestyles, economic pursuits, etc.), form the essential source around which the supply and demand of electricity revolve. This makes it possible to analyse trends and evaluate the energy-related policies of both urban and rural areas. Within the region, the province of Foggia (with the greatest rural characteristics, covering 35.9% of the regional surface area) has the lowest density level, with a value of 86.0 inhabitants per km2. The Municipality of San Severo's territory is larger than the province's average, with an area of 336.31 km^2 and a population density of 148.20 people/km^2. As of January 1, 2022, the municipality of San Severo has 49,843 persons living in 20,338 homes. As shown in Table 3 below, the average number of members per household is 2.45, which is slightly higher than the 2.3 average for the entire country.

Table 3. Demographic indices

RESIDENT POPULATION BY GENDER. Census 2022. Absolute values.					
Year	Province	Municipality	Resident population		
2022			Males	Females	Total
	Foggia	San Severo	24.360	25.483	49.843

AVERAGE NUMBER AND SIZE OF FAMILIES, RESIDENT POPULATION							
Year	Province	Municipality	Families		Resident population		Total
			Number	Average size	in the family	cohabitation	
2019	Foggia	San Severo	19.539	2,52	49.315	181	49.496
2022	Foggia	San Severo	20.338	2,45	49.843	-	49.843

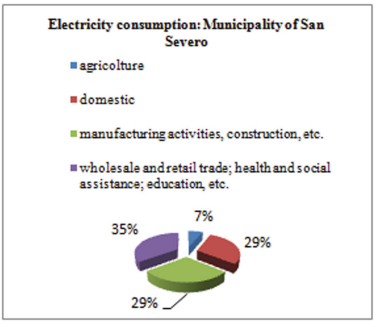
b) Energy data analysis:

For the comprehensive review of the demand energy system, energy consumption data for the year 2022 [31] were examined and processed based on the province of Foggia's per-capita electricity consumption relative to the population of the municipality of San Severo, divided into user categories (sectors). The estimated result was approximately 153. 82 GWh (refer to Table 4 below).

Using the analysed data, an energy balance for the current state may be created by quantitatively examining the energy flows that are used in the Municipality of

Table 4. Electricity consumption for Foggia and San Severo Municipalities

PROVINCE OF FOGGIA					
ELECTRICITY CONSUMPTION/year					
year	AGRICULTURE GWh	DOMETISC GWh	INDUSTRY GWh	SERVICES GWh	TOTAL CONSUMPTION GWh
2022	agricolture	domestic	manufacturing activities, construction, etc.	wholesale and retail trade; health and social assistance; education, etc.	
	118,5	543,3	537,1	649,8	1848,7



PERSONAL DATA(Istat 2022)		
	n. of inhabitants	n. of families
Prov. Foggia	599028	
San severo	**49843**	**20338**

MUNICIPALITY OF SAN SEVERO					
ELECTRICITY CONSUMPTION/year					
year	AGRICULTURE GWh	DOMETISC GWh	INDUSTRY GWh	SERVICES GWh	TOTAL CONSUMPTION GWh
	AGRICULTURE GWh	domestic	manufacturing activities, construction, etc.	wholesale and retail trade; health and social assistance; education, etc.	
2022	9,86	45,21	44,69	54,07	153,82

AVERAGE CONSUMPTION FOR DOMESTIC USE					
Population/families			Electricity consumption per inhabitant/year in kWh	Electricity consumption per family/year in kWh	Overall electricity consumption
year	number of families	average size	Kwh/year	Kwh/year	Kwh/year
2022	20338	2,45	907,50	2223,38	45219000,75

AVERAGE CONSUMPTION FOR AGRICULTURAL USE					
Land use of the agricultural unit - Used agricultural area (sau)					
agricultural units	arable land	vine	agricultural woody crops, excluding vines	family gardens	permanent meadows and pastures
surface-hectares	20259,2	3972,4	4009,9	15,8	393,9
Electricity consumption per hectare/year in kWh	344.15 Kwh/hectare/year (average value)				

San Severo. About 29% of the total is consumed at home, which is higher than what is consumed in industry. The agriculture industry necessitates 7% of all the power that is used. As a result, it is evident that the local level consumption of electricity, at 55.07 GWh, is larger when the household sector's consumption is added to the agricultural sector's (36%). While the typical home uses around 2,223.38 kWh of power annually, the per capita consumption of electricity per inhabitant is 907.5 kWh. The energy consumption shared by the agricultural and domestic sectors has been converted to CO2eq, according to the equivalent emission factor for the national gross thermoelectric production, with an estimated average value of 415.5 g CO2/kWh [32].

As a result, together, both sectors produced 228. 853.2 tCO2 equivalent greenhouse gas emissions in 2022. This is because of the concentration of population density and activities on the territory, which means that all cities are responsible for most energy consumption-related emissions.

3.4 The Project Scenario: The Agro-Urban Park

The project scenario, which derives its physicality from the land and connects regional and local spatial planning projections, is described in this section, based on the aforementioned assessments. Following the General Urban Plan (PUG), which promotes a corridor of public green space known as "the Green Walls" separating the urban area and serving as a link between the city and the countryside, the aim is to devote a portion of the land in the southern part of the Municipality of San Severo to the development of an "agro-urban park" (Fig. 5).



Fig. 5. Source: PUG Programmatic Part: Implementation of the Strategic Plan, City-Country Pact (PUG Table 4)

This scenario brings along the complexity of a city with an "uncertain urban identity in which the lack of homogeneous and coherent reference systems is felt, especially in the peripheral fringes" (PUG, 2019) and aims at transforming the indeterminacy of a peripheral part of the territory (peri-urban) into an opportunity, thus declining the concept of the "City of the Future" (COM(2014) 490): European cities must be (…) green, ecologically and environmentally regenerative places: (…) European urban spatial development must (…) enjoy a high level of environmental protection and quality in the areas surrounding cities [33]. In fact, according to the European guidelines [34] "*Bearing in mind both endogenous and exogenous factors, the sustainability and resilience of cities and regions cannot be addressed separately. This can be achieved through functional partnerships between urban and rural areas and through integrated projects aimed at enhancing the*

sustainability and resilience of the local economic, social and environmental systems of cities, their functional areas and their rural periphery".

With regards to design, the scenario consists of strategies and activities that refer to the 'Urban Margin Scheme' of the PUG City-Country Pact, to appropriate actions and to a system of relations:

a) Specific actions.

The project area (about 3.1 hectares, Fig. 6) has been split up into macro-sites, two of which will be kept as public spaces for social interactions and recreational activities while also serving as areas for the preservation of olive trees and other fruit-bearing plants. The third area is designed for productive-multifunctional agriculture. It includes urban gardens, social and didactic orchards, and an agri-voltaic system, which maximizes the integration of energy production and agrarian systems in order to promote multi-functional activity. Urban gardens serve as a primary productive activity, which is a prerequisite for the existence of agrarian use.

The project's added value is thus twofold: firstly, it aims to reorganize virtuous farming practices, which in turn leads to the recognition of the same rural, peri-urban areas as catalyst for a network of social, commercial and recreational activities as well as environmental benefits related to the greening of the city and the management of resources [35]. Secondly, it produces energy from renewable sources (solar) for community consumption and self-consumption, a model also known as renewable energy communities (RECs).

b) Relationship system.

With this initiative, the promotion of the network of zero-kilometre short supply chains and the relationship between town and country are developed and enhanced, by guarantying the following aspects:

- connections oriented to the rural-naturalistic enjoyment of the area; - sales of quality agricultural products in the peri-urban area; - public areas for recreational and social events; - places for environmental education; - improved relationship between city, citizens and environment; - direct access from the city to promote the use of the park

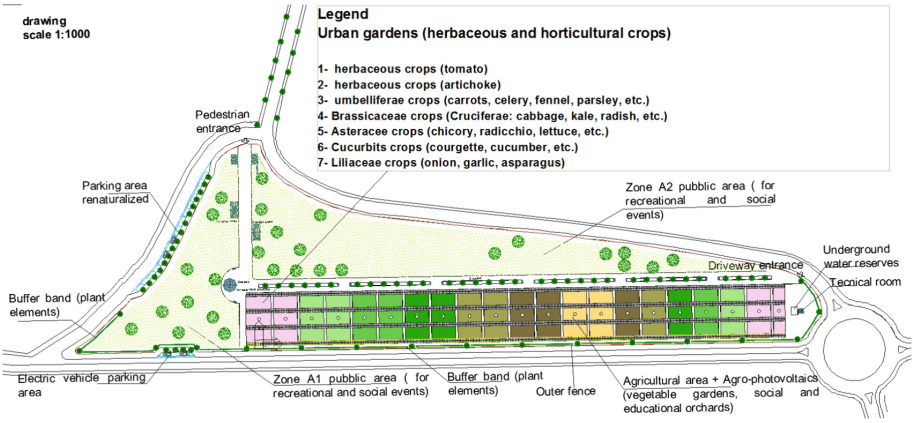


Fig. 6. Project "agro-urban park"

and the sale of local agricultural products, aimed at bringing agriculture and local consumption closer together.

Therefore, the agro-voltaic system's producibility within the agro-urban park (Fig. 7) is calculated as an annual electricity production of 922,030.2 kWh, which will be used for energy sharing as well as for self-consumption (area operation). This will benefit about 411 households by reducing their greenhouse gas emission by 3,831 tCO2 equivalent (Table 5).

Project: agro-urban park				
overall area of the site			**mq**	**31000,00**
Agricultural volume (or pore space)				
surface occupied by the agrivoltaic system	330,00	32,00	mq	10560,00
minimum height of the photovoltaic modules with respect to the ground		2,10		
total			**mc**	**22176,00**
Total footprint of the agrivoltaic system (Spv)				
number of panels		1312		
photovoltaic modules dimensions (active surface including frame)	1,10	1,80		
total			**mq**	**2597,76**
LAOR (Land Area Occupation Ratio): LAOR< 40%				
ratio of the total footprint of the agrivoltaic system				**0,25**
Nominal power system agrivoltaic				
number of panels		1312		
Rated power of each photovoltaic module	Watt	360		
			kW	**472,32**
Photovolatic electricity production (FVstandard)			**GWh/year**	**0,92**
The values for the average annual production were processed through the Photovoltaic Geographical Information System (PVGIS) of the European Commission, https://re.jrc.ec.europa.eu/pvg_tools/en/			**kWh/year**	**922030,02**

Fig. 7. Project "agro-urban park"

Table 5. Energy balance ex-post

ENERGY BALANCE EX- POST (Kwh/year)								
year	activity	energy consumption (Kwh/year)	year	agro-urban park (energy production kWh/year)	self-consumption for agricultural use	energy communities (energy sharing)	number of families (CER)	reduction of overall energy consumption in the area
2022	Agriculture	9860000,0	2024	922.030,2	1066,87	/		9858933,13
2022	Domestic	45219001,0	2024		/	920963,33	411,44	44298037,67

INVENTORY OF CO2 EMISSIONS			
	Agriculture (tCO2)	Domestic (tCO2)	Total (tCO2)
2022	40968,3	187884,9	228853,2
2024	40963,9	184058,3	225022,2
CO2 emissions saving			**3831,0**

4 Conclusion

Based on a multifunctional model of peri-urban agriculture and the use of eco-sustainable systems (agro-photovoltaic) for the production and sharing of locally generated energy from renewable sources, the project scenario offered some design ideas and, at a preliminary level, identified the theme of eco-systemic management of a peri-urban area in the municipality of San Severo.

High-quality agricultural output associated with multifunctionality, particularly in urban gardens, is sometimes seen as a niche phenomenon or as being small scaled. Over the past eight years, the proportion of Italian municipalities managing their green spaces including urban gardens has increased by 43% [36].

In this regard, the project scenario presented here aims to sketch a tangible and plausible alternative framework for the dismantling of agriculture and the surrounding rural areas, beginning with the development of new coalitions among industry participants, the public and institutions, especially in peri-urban contexts.

In contrast, the project scenario includes the concept of participation and the creation of an energy community open to all consumers in the neighborhoods that border the project area, including those who belong to low-income or vulnerable families, with regard to the topic of agri-voltaic energy production from renewable sources. Communities that rely on self-consumption and renewable energy sources have the potential to significantly accelerate the energy transition. An increasing number of local governments, residents and farmers can actively participate in the energy system as a result of the decentralization of energy production. This enables maximizing self-consumption and creating local advantages (such as lowering greenhouse gas emissions and using local energy sources) by taking full use of the opportunities presented by distributed generation.

Specifically, within peri-urban agricultural areas, agriculture assumes a landscape-environmental value that represents a form of active protection against land consumption on the part of the city. This idea of agriculture is proposed to produce not only primary

goods but also “public goods”, in terms of environmental and landscape quality and availability of public spaces, as well as in terms of service and territorial protection and valorization [37].

References

1. European Committee of the Regions (CoR): EU annual report, The state of regions and cities (2023). https://cor.europa.eu/en/engage/brochures/Documents/EU%20Annual%20Report%20on%20the%20State%20of%20Regions%20and%20Cities%202023/4892%20-%202023%20Annual%20Report%20it.pdf. Accessed 02 Feb 2024
2. National System for Environmental Protection, Land consumption, territorial dynamics and ecosystem services, Report-SNPA n. 37/2023, Rome (2023). ISBN 978-88-448-1178-5
3. Donadieu, P.: Sciences du paysage. Entre théories et pratiques, Editions TEC & DOC - Lavoisier, Paris (2012)
4. Opinion of the European Economic and Social Committee, Peri-urban agriculture, (2005/C 74/12), Brussels (2004)
5. Gisotti, M.R., Peri-urban landscapes: reading, description, project - Territories n. 15, Florence University Press, Florence (2012)
6. Territorial Agenda 2030, A future for all places, Germany (2020). https://territorialagenda.eu/wp-content/uploads/TA2030_jul2021_it.pdf. Accessed 02 Feb 2024
7. European Commission, The European Green Deal, COM (2019) 640, Brussels (2019)
8. United Nations General Assembly, 2030 Agenda for Sustainable Development, New York, United States (2015)
9. United Nations Framework Convention on Climate Change (UNFCCC), Paris Agreement, 2015. https://eur-lex.europa.eu/legal-content/IT/TXT/PDF/?uri=CELEX:22016A1019(01). Accessed 25 01 2024
10. International Panel on Climate Change IPCC, Climate Change 2023, Report AR6, The Working Group III contribution to the Sixth Assessment Report: Mitigation of Climate Change 2022. https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/. Accessed 25 Jan 2024
11. Magnaghi, A., The rule and the project. a bioregionalist approach to territorial planning - Territories n. 15, Florence University Press, Florence (2014)
12. Directive (EU) 2018/2001, The promotion of the use of energy from renewable sources, Brussels (2018)
13. Passarelli, D.: The Challenges of Urban Planning Today. INU Editions, Rome (2022)
14. Toledo, C., Scognamiglio, A.: Agrivoltaic systems design and assessment: a critical review, and a descriptive model towards a sustainable landscape vision (three-dimensional agrivoltaic patterns). Sustainability **13**, 6871 (2021). https://doi.org/10.3390/su13126871. Accessed 10 Feb 2024
15. Ministry of Ecological Transition (MiTE), Guidelines on Agrivoltaic Systems, Rome (2022)
16. Apulia Region, resolution of the Regional Council of 2 August 2018, n. 1424, which updates the PEAR (Regional Environmental Energy Plan), Bari (2018)
17. European Commission, Prospects for the common agricultural policy, Green Paper, COM(85) 333, Brussels (1985)
18. Cooper, T., Hart, K., Baldock, D.: Provision of Public Goods Through Agriculture in the European Union, Report for DG Agriculture and Rural Development, Institute for European Environmental Policy, London (2009)
19. European Commission, The future of food and agriculture, COM(2017) 713, Brussels (2017)
20. Council of Europe, European Landscape Convention, Florence (2000)

21. Regulation (EU) 2021/2115, establishing rules on support for strategic plans to be drawn up by Member States under the common agricultural policy (CAP Strategic Plans), Brussels, (2021)
22. European Commission, Implementing Decision, approving Italy's CAP strategic plan 2023–2027 for the purposes of supporting of the Union financed by the European Agricultural Guarantee Fund and the European Fund agriculture for rural development, C(2022) 8645, Brussels (2022)
23. Apulia, resolution of the Regional Council of 5 December 2022, n. 1788, Regional complement for Rural Development (CSR) of the 2023–2027 CAP strategic plan of the Puglia Region, Bari (2022)
24. European Commission, Energy for the Future: Renewable Energy Sources, White Paper for a Community Strategy and Action Plan, COM(1997)599, Brussels (1997)
25. European Commission, Stepping up Europe's 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people, COM(2020) 562, Brussels (2020
26. Decision of the European Council on 13 July 2021, National Recovery and Resilience Plan (PNRR), strategic document that the Italian Government has prepared to access funds for the post-pandemic European recovery (Recovery Plan) of the Next generation EU (NGEU) programme, Brussels (2021)
27. Ministry of the Environment and Energy Safety, Integrated National Plan for Energy and Climate 2030 (PNIEC), prepared by Italy in implementation of Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018, transmitted to the European Commission on 31 December 2019, Rome (2020)
28. Apulia Region, resolution of the Regional Council of 16 February 2015, n. 176, Regional Territorial Landscape Plan (PPTR) of the Apulia Region, Bari (2015)
29. Municipality of San Severo, City Council Resolution no. 26 of 04.05.2019, adaptation of the General Urban Plan (PUG) to the Regional Territorial Landscape Plan (PPTR), San Severo (2019)
30. National Institute of Statistics (Istat), Resident Population and Demographic Dynamics, Rome (2022)
31. TERNA S.p.A., Statistical Yearbook, Electricity in the Regions, Roma (2022)
32. Higher Institute for Environmental Protection and Research (ISPRA), Efficiency and decarbonisation indicators of the national energy system and the electricity sector, Report 343/2021, Rome (2021)
33. European Commission, The urban dimension of EU policies – Building blocks of an EU Urban Agenda, COM(2014) 490, Brussels (2014)
34. Opinion of the European Economic and Social Committee – Review of the EU Territorial Agenda, of Leipzig Charter and Urban Agenda for the EU, 2020/C 429/20, Brussels (2020)
35. Ilieva, R.T.: Urban Food Planning: Seeds of Transition in the Global North. Routledge, London (2016). https://doi.org/10.4324/9781315658650, ISBN 9781138998483
36. Borsotto, P.: Agriculture and society: urban gardens. In: Yearbook of Italian Agriculture 2018, vol. LXXII (2019)
37. Treu, M.C.: The urban matrix and the soil matrix. Knowledge tools to guide choices settlement and production, Report presented to Strumenti. Plans and Projects for a new urban-rural dimension. AIIA-R.U.R.A.L.I.A., Imola (2010)

Potential of the 15-Minute Peripheral City: Identifying Main Streets and Population Within Walking Distance

Joan Perez(✉) and Giovanni Fusco

Université Côte-Azur, CNRS, AMU, AU, ESPACE, Nice, France
joan.perez@univ-cotedazur.fr

Abstract. The concept of the 15-minute city presents challenges for pedestrian accessibility, particularly in peripheral areas with less pedestrian-friendly street networks. This paper explores the angular continuity of main streets and the population potential around them as crucial elements for the development of the 15-minute peripheral city. By utilizing geoprocessing algorithms, the study aims to identify main streets and verify their demographic potential in two distinct geographic contexts near Lille and Nice, France. The protocol is divided into four steps, as follows: (1) main streets identification through continuity, (2) calculation of morphological indicators on buildings, (3) machine learning to estimate the number of dwellings per building, and (4) population potential estimate within different walking distances from main streets. The findings reveal a network of interconnected main streets with significant population potentials in the outskirts of both test areas. These streets could serve as the development corridors for enhancing commercial activities and services, supporting the vision of the 15-minute city in peripheral areas.

Keywords: 15-minute city · street network · catchment area · pedestrian accessibility · angular continuity

1 Introduction

The 15-minute city poses a challenge to pedestrian accessibility, particularly in the outskirts and peripheries where the street network is less pedestrian-friendly. The Evolutive Meshed Compact City (emc2) project proposes a new model of the 15-minute city for the loose structural networks of peripheral location (Fusco et al., 2023). It envisages compact urban forms as corridor developments based on existing main roads, forming a meshed structure within metropolitan areas. The emc2 project is currently working on the characterization of morphological and demographic preconditions for these developments. The present paper is a first proposal in this direction, focusing on two specific aspects: angular continuity of main streets and population potential in a wider area around them. Indeed, in addition to numerous challenges for the 15-minute city to work effectively, such as inclusive urban design exemplified by the creation of walkable neighborhoods, conditions must be met for the presence of retail and services. Building on

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 50–60, 2024.
https://doi.org/10.1007/978-3-031-65238-7_4

the theory of natural movement (Hillier et al. 1993), the emc2 model considers a first requirement the existence of a well-connected foreground network of main streets, where retail and services can cluster. However, this begs the question of the potential demand within a walking catchment area, to ensure the presence of proximity-based activities. It becomes thus important to both identify possible elements of the foreground network of main streets and verify that they benefit from the demographic potential to become the backbone of the 15-minute peripheral city. Specific geoprocessing algorithms are needed to achieve these goals, as those presented and discussed within this paper.

For this paper, we decided to focus on two distinct geographic contexts situated on the outskirts of the metropolitan areas of Lille and Nice, in northern and southern France, respectively. The considered outskirt of Lille is made of the following 4 municipalities: Santes, Hallennes-lez-Haubourdin, Haubourdin, and Emmerin, totally accounting for 27.993 inhabitants 22.2 km^2; while within the outskirt of Nice we focused on the municipalities of Drap, Cantaron and La Trinité accounting for 16.572 inhabitants over 27.8 km^2. Building footprints, roads, and administrative boundaries are extracted from the version 3.3 of the French dataset BD TOPO® (IGN, 2023). These two case studies provide interesting geographical differences: a flat terrain with a tradition of linear developments around Lille as opposed to a more constrained hilly landscape where topography induces linear developments around Nice (Fig. 1).

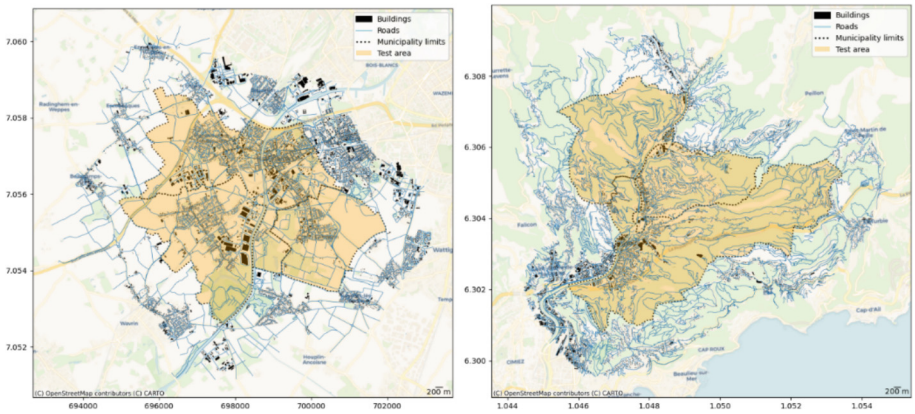


Fig. 1. Test areas, the municipalities of Santes, Hallennes-lez-Haubourdin, Haubourdin, and Emmerin in the the outskirt of Lille (left) and Drap, Cantaron and La Trinité in the outskirt of Nice (right)

A buffer of 1200 m (see catchment areas Sect. 5) has been performed over the administrative boundaries of the test areas in order to include 37.985 buildings and 6.157 road segments in the Lille outskirt, and 24.001 buildings and 6.179 road segments in the Nice outskirt. Highways and highway ramps are manually filtered out of the dataset, as they cannot play the role of pedestrian-friendly main streets for the 15-minute city. In addition, dual carriageways are re-digitized as single carriageways to improve the performances of the identification of main streets (Sect. 2). This paper is organized as follows. Section 2 presents the identification of main streets through an improvement

of the *Morpheo*'s algorithm. Section 3 focuses on the computation of morphometric indicators over buildings. Section 4 uses machine learning (classification + regression) to estimate the number of dwellings per building. Section 5 estimates the population potential around the identified main streets through catchment areas consistent with the 5, 10 and 15 minute-city. Section 6 concludes the paper with a discussion regarding future improvements of the protocol. Input data and the protocol are fully reproducible and available (see Sect. 6).

2 Main Streets Through Continuity

Angular continuity is useful for defining main streets and is normally assessed through intersection continuity negotiation algorithms (Porta et al., 2006). The QGIS plugin *Morpheo* (Lagesse, 2015) proposes a specific algorithm to assemble angularly continuous street segments in new objects called "ways" (i.e. natural streets, Stavroulaki et al. 2017) and hierarchizes them through connectivity measures. Aggregation of street segments uses deletion buffers at segment intersections and deviation angles. After applying the *Morpheo* plugin with the preconized parameters (deletion buffer of 4 m, deviation angles of 60°) over the two test areas, we obtain 1.891 ways for the outskirt of Lille, and 2.006 for the outskirt of Nice. Our proposal extends *Morpheo*'s algorithm, acknowledging that peripheral areas normally have ways with lower values of connectivity than those in central areas. To identify main streets in a local context, we introduce a novel indicator considering the connectivity of surrounding ways: the local relative connectivity (CONN_LocRel). Its purpose is to identify ways with connectivity levels significantly different from their immediate surroundings, highlighting potential connectivity anomalies which become focal elements in local contexts. Prior to calculating the local relative connectivity, two indicators must be calculated.

$$\mathrm{CONN}_{\mathrm{LocSum}} = \sum_{i=1}^{n} \mathrm{CONN}_{\mathrm{i}}$$

$$\mathrm{CONN}_{\mathrm{LocAvg}} = \frac{\mathrm{CONN}_{\mathrm{LocSum}}}{n}$$

$$\mathrm{CONN}_{\mathrm{LocRel}} = \frac{\mathrm{CONN}}{\mathrm{CONN}_{\mathrm{LocAvg}}}$$

where CONNi represents the sum of connectivity values associated with each intersecting buffer, n the number of intersecting ways and CONN the connectivity value of a given way.

The first indicator is the sum of the connectivity values associated with all intersecting buffers for each way identified by *Morpheo*. This indicator, named CONN_LocSum, reflects the overall level of connectivity of all the elements directly connected to a given way. Moving on, the second indicator, CONN_LocAvg, considers the number of intersecting ways when calculating connectivity, thereby providing a weighted average connectivity value for each of them. Finally, the local relative connectivity (CONN_LocRel) is calculated through standardization by CONN_LocAvg. This indicator evaluates connectivity relative to the local connectivity context, allowing for the identification of elements with disproportionately high values compared to neighboring elements.

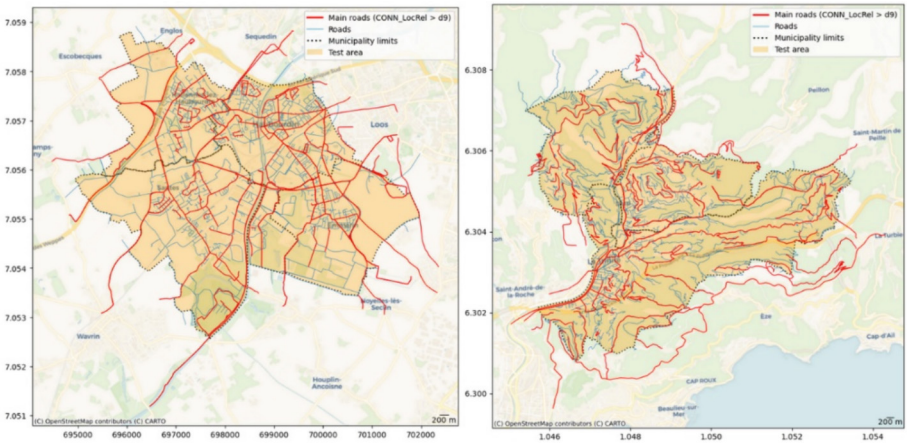


Fig. 2. The main roads in the outskirt of Lille (left) and Nice (right)

Figure 2 illustrates the identification of the main streets in the test areas within the test regions by mapping the ways characterized by a CONN_LocRel value falling within the 10th decile. In both the outskirts of Lille and Nice, results appear consistent with a successful identification of ways with high connectivity values compared to neighboring ways. These streets will serve as the focal elements for aggregating population potential, as outlined in Sect. 5. In Lille, the D9 value is 1.26, whereas in Nice, it is 1.33. Populations will be estimated from dwelling data. However, the number of dwellings is not available for some buildings (see further), which forces us to first implement some morphological indicators (Sect. 3) to assign them an estimated number of dwellings.

3 Morphological Indicators

This section is about the calculation of diverse indicators associated with building morphology. The goal is to collect enough morphological indicators to subsequently assess whether a building contains dwellings or not (Sect. 4). The premise is that buildings with dwellings, whether entirely residential or mixed-use, exhibit distinct morphological characteristics compared to non-residential structures (Steadman 2014, Araldi et al. 2023, Perez et al., 2024). For instance, industrial and logistic buildings often have larger footprints, while their shapes may demonstrate reduced elongation and high convexity, reflecting specific requirements related to their function. Basic indicators, such as surface areas or perimeters are computed using *geopandas*. For advanced indicators, like the ratio of shared walls or the elongation of each building, we use the urban morphology toolkit *momepy*, a library for quantitative analysis of urban form developed by Fleischmann (2019).

We also derive three composite indicators, based on the basic metrics previously calculated. The first, denoted FA (Floor-Area) is the product of floor and area (F.A). ECA (Elongation-Convexity-Area), is made to discern sizable yet non-elongated specialized structures/instances often characteristic of non-residential buildings, distinct

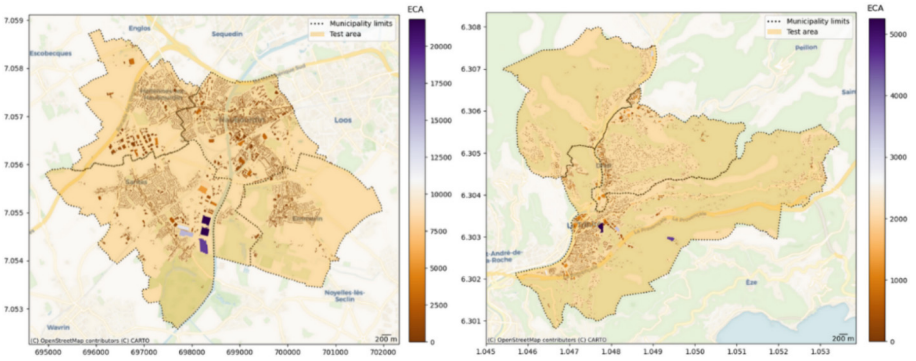


Fig. 3. ECA (Elongation-Convexity-Area) values per building in both test areas

from elongated modernist residential complexes.

$$\mathrm{ECA} = (1 - \mathrm{E}).\mathrm{C}.\mathrm{A}$$

As displayed in Fig. 3, large sized but yet non-elongated buildings are well detected by the ECA indicator. Then, EA (Elongation-Area), which is the product of surface area and elongation (E.A), shall assume significance in estimating the number of dwellings per building. The final feature attributes of the dataset are as follows: F (number of floors), A (surface area of the building footprint), P (perimeter), E (elongation), C (convexity), FA (floor-area), ECA (elongation-convexity-area), EA (elongation-area) and SW (shared walls).

4 Dwellings Estimation

The goal of this section is to estimate the number of dwellings per building based on the morphometry indicators that have been calculated in the previous section. We proceed with two main tasks: classification for evaluating the presence of dwellings and regression for estimating the number of dwellings.

For classification, we use a decision tree classifier to predict whether a building has dwellings or not, based on its morphology indicators. The attribute data from the BD TOPO® contains the number of dwellings per building. Yet, this feature is incomplete. For example, in the Lille subset, 45.93% of the information is missing, while in Nice it reaches 60.11%. We isolate these buildings. Subsequently, for the remaining buildings, a binary encoding is applied: buildings without dwellings are assigned a value of 0, while buildings with dwellings are assigned a value of 1, irrespective of the actual count of dwellings within each building. The datasets for Lille and Nice are partitioned into training (70%) and testing (30%) subsets.

The trained model's accuracy is then evaluated against the test subset using confusion matrices. The proportion of correctly classified instances reaches 95.49% for the subset in Lille, and 87.95% for the subset in Nice, which indicated a relatively good overall performance of the decision tree classifier. Other performance metrics are provided in Table 1, such as the complexity parameter, the number of splits, predicted and

Table 1. Decision tree classifier performance metrics for Lille and Nice subsets

Complexity Param	N_Splits	Predicted	Expected	Accuracy
Lille subset				
0.658247	0	1	0.1818	0.9595
0.040183	1	0	0.0572	
0.017986	3	1	0.0629	
0.015308	5	0	0.0299	
Nice subset				
0.322142	0	1	0.2089	0.8865
0.051785	1	0	0.3347	
0.029285	3	1	0.0922	
0.010000	5	1	0.1176	

expected values. As the number of splits increases, the model becomes more specific in its predictions.

Table 2. Decision tree classifier: variable importance for Lille and Nice subsets

Feature	Lille subset	Nice subset
FA	35	33
A	26	24
P	26	21
FL	8	6
ECA	2	8
EA	2	8
E	1	0
SW	0	0

As evidenced in Table 2, Floor-Area, Area and Perimeter emerge as the most influential variables in determining the presence of dwellings within buildings, with ECA, EA and FL contributing less often, i.e. for more specific subsets of buildings. The models' performance is considered sufficiently robust to extend their application to buildings with missing information regarding dwelling presence, which were identified earlier in this section. The next step is to estimate the number of dwellings for buildings that lack information but have been identified as possessing dwellings by the decision tree classifier. Those buildings are temporarily isolated. Subsequently, we set up a repeated k-fold cross-validation framework to train a stepwise regression model using the *leapBackward* method from the caret library (Kuhn, 2023). The morphology indicators are used as predictors, while the target variable is the number of dwellings.

As the maximum number of variables allowed and incorporated into the regression model increases (nvmax), there is a trend of decreasing Root Mean Squared Error (RMSE) and increasing coefficient of determination (R^2). However, this improvement is marginal. Notably, in Nice, there is a clear advantage in using two regressors, whereas a single regressor suffices for Lille. Table 3 illustrates this fact, also showing slightly higher RMSE values in the Nice subset compared to the Lille subset, accompanied by

Table 3. Stepwise regression performance metrics

	Nice subset			Lille subset		
nvmax	RMSE	R^2	MAE	RMSE	R^2	MAE
1	4.422	0.724	1.324	2.056	0.771	0.654
2	4.100	0.755	1.814	2.062	0.771	0.639
3	4.135	0.751	1.805	2.085	0.765	0.646
4	4.058	0.759	1.732	2.051	0.775	0.631
5	4.065	0.759	1.719	2.040	0.777	0.666
6	4.066	0.759	1.718	2.050	0.775	0.688
7	4.052	0.760	1.705	2.027	0.779	0.705

lower R^2 values, suggesting slightly better accuracy in Lille. However, with R^2 values above 0.7 in both models, the overall performance indicates that the model is effective in estimating the number of dwellings per building.

Table 4. Stepwise regression variable importance

nvmax	FL	A	P	E	C	FA	ECA	EA	SW
Lille subset									
1						*			
2						*		*	
3						*	*	*	
4		*				*	*	*	
5	*	*				*	*	*	
6	*	*	*			*	*	*	
7	*	*	*	*		*	*	*	
Nice subset									
1						*			
2	*					*			
3	*	*				*			
4	*	*				*	*		
5	*	*		*		*	*		
6	*	*	*	*		*	*		
7	*	*	*	*	*	*	*		

Table 4 indicates that both in Lille and Nice, the floor-area (FA) holds the highest predictive power among regressors. However, as Table 3 indicates that a second regressor is needed in Nice to obtain satisfactory predictive power, both floor (FL) and floor-area (FA) will be included in the model. From Table 3, we also know that any additional regressor will only have a marginal effect in Lille. To use a single model, FA and FL will be used both for Lille and Nice. We then generate predictions for the number of dwellings and ensure that negative predictions (resulting from sparse data) are adjusted to 0. Finally, the estimated dwelling numbers are assigned to buildings lacking information about dwellings but identified as possessing dwellings by the decision tree classifier.

5 Catchment Areas and Population Potentials

This section focuses on estimating the population potential within catchment areas around main axes. It begins by importing the main streets as identified as the 10th decile from the Relative Connectivity indicator in Sect. 2 and the buildings with the estimated number of dwellings from Sect. 4. Catchment areas are created around the main roads using buffers of 400, 800 and 1200 m. 400, 800 and 1200 m roughly corresponds to 5, 10 and 15 min of walking time for able-bodied adults. Population potential per building is then calculated based on the estimated number of dwellings, considering an average household size of 1.92 for collective housings and 2.44 for single-family homes in France (Léger, 2019). The methodology aggregates the population count of each building to the catchment areas within the three specified catchment radii. Values are subsequently spatially joined to the main roads thus providing population potential along the latter as highlighted below.

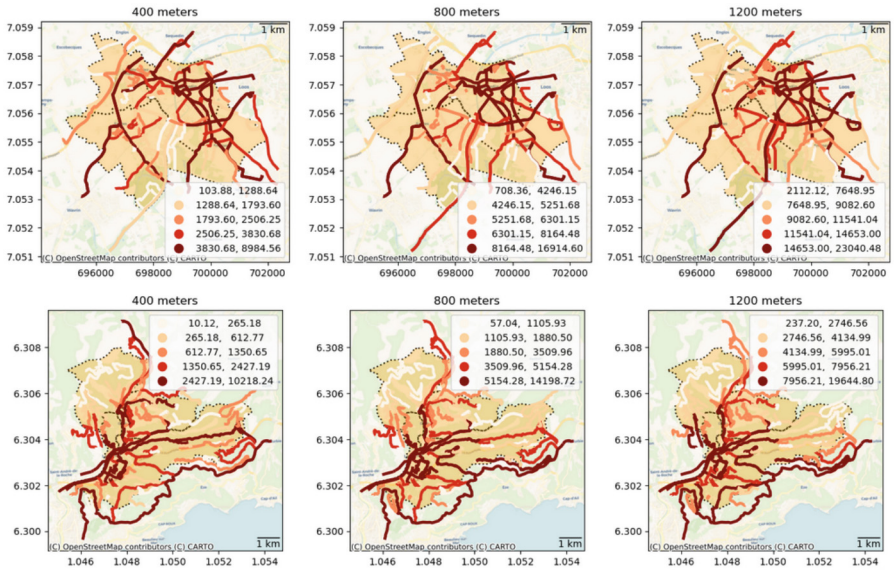


Fig. 4. Population potentials along main axes in the outskirt of Lille (top) and Nice (bottom) for catchment radii of 400, 800 and 1200 m

Figure 4 also shows that a meshed structure of main streets clearly appears in the outskirts of Lille. Main streets also stand out on the outskirts of Nice but due to the topology and to numerous valley dead ends, a meshed structure is less evident. The relative population potentials, standardized per kilometer of road (Fig. 5), highlight focal elements and smaller meshed streets with high demographic potential for the development of the emc2 model.

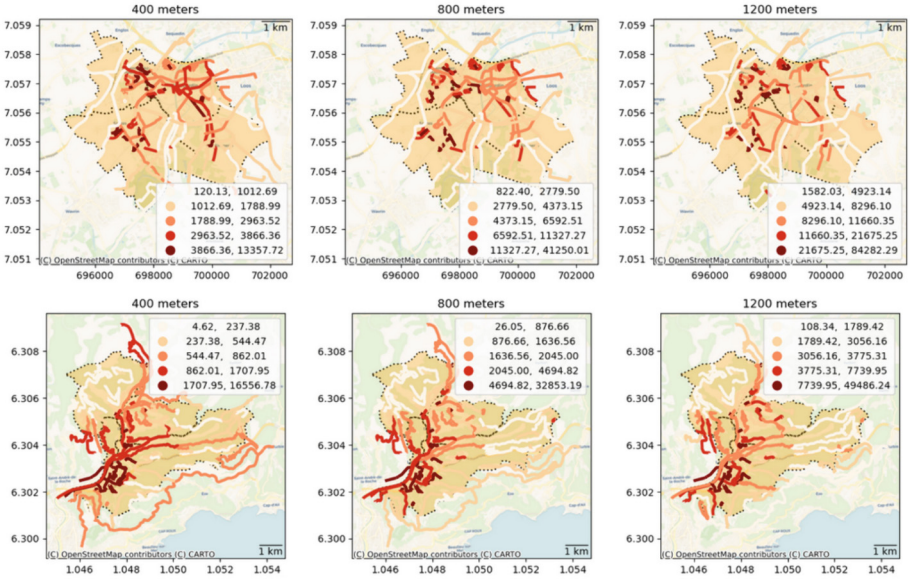


Fig. 5. Population potentials per kilometer of road along main axes in the outskirt of Lille (top) and Nice (bottom) for catchment radii of 400, 800 and 1200 m

6 Catchment Areas and Population Potentials

The findings are in line with the real-world situations in both the outskirts of Lille and Nice and with our intended objective: identifying a network of interconnected main streets with population potential conducive to targeted densification efforts. These identified main streets could serve as the backbone for enhancing commercial activities, services, and amenities in the area. Yet, we stress the importance of investigating other factors, such as population heterogeneity or kinds of services/retail activities. The protocol has been made available on GitHub (Appendix 1) and the datasets for Lille and Nice on Zenodo (Appendix 2). On Zenodo, both inputs and outputs are available within two GeoPackages. The protocol is divided into 4 main steps and one appendix as follows: (1) the identification of main streets - R Script (2) morphometry on buildings – Python script (3) evaluation of the number of dwellings within inhabited buildings – R Script (4) projecting population potential to main streets – R Script (Appendix) thematic maps presented in this paper – Python script.

The protocol outlined in this paper represents an exploratory phase, providing preliminary results derived from two extremely different geographical contexts. It is clearly subject to several improvements that we would like to discuss in what follows. Firstly, angular continuity analysis shall be combined, or replaced by configurational analysis that is used to identify what is described as the foreground network (i.e. main streets) in space syntax research; Hillier, 1996). The latest research highlights the importance of the urban environment's configurational characteristics for the 15-minute city at all scales (Murgante et al., 2024). More specifically, the multiscale configurational protocol proposed by Berghauser Pont et al., (2019) allows for the identification of local main

streets with no regards to the street typology. Since we manually filtered highway and highway ramps (Sect. 1), configurational analysis could significantly improve the protocol. Second, the morphology indicators could be calculated at different spatial lags to add indicators for the classification and regression models. Spatial lags could help detect buildings that are exceptions amongst local areas. Third, the null hypothesis of complete spatial randomness (CSR) shall be tested regarding the distribution of buildings with missing values of dwellings. Fourth, the estimation of the number of dwellings per building could be improved with, for example, using a count regression model for which the value zero cannot occur, such as the zero-truncated Poisson or negative binomial regressions. The population assigned to the different dwelling types could also be calculated with more place specific data and should be validated with available disaggregated census data to consider the presence of dwelling units used as secondary homes. Lastly, while catchment areas are currently calculated using Euclidean distance, employing network distance would yield more precise outcomes, given that individuals walk along paths and streets.

Acknowledgments. This paper is part of the emc2 project, which received the grant ANR-23-DUTP-0003–01 from the French National Research Agency (ANR) within the DUT Partnership.

Appendix 1

https://github.com/perezjoan/emc2-WP2/tree/main.

Road continuity - Dwellings - Population - Catchment areas/ICCSA protocol version.

Appendix 2

https://zenodo.org/records/10946415.

15-minute city, street network, catchment area, pedestrian accessibility, angular continuity.

This upload contains two Geopackage files of raw data used for urban analysis in the outskirts of Lille and Nice, France. The data include building footprints (layer "building"), roads (layer "road"), and administrative boundaries (layer "adm_boundaries") extracted from version 3.3 of the French dataset BD TOPO®3 (IGN, 2023) for the municipalities of Santes, Hallennes-lez-Haubourdin, Haubourdin, and Emmerin in northern France (Geopackage "DPC_59.gpkg") and Drap, Cantaron and La Trinité in southern France (Geopackage "DPC_06.gpkg").

References

Araldi, A., Emsellem, D., Fusco, G., Tettamanzi A., Overal D.: Building types in France. Clustering building morphometrics using national spatial data, Revue Internationale de Géomatique **31**(3–4), 265–302 (2023). ISSN 1260-5875, https://doi.org/10.3166/rig31.265-302

Berghauser Pont, M., et al.: The spatial distribution and frequency of street, plot and building types across five European cities. Environ. Plann. B: Urban Anal. City Sci. **46**(7), 1226–1242 (2019)

Fleischmann, M.: Momepy: urban morphology measuring toolkit. J. Open Source Softw. **4**(43), 1807 (2019). https://doi.org/10.21105/joss.01807

Fusco, G., Berghauser Pont, M., Cutini, V., Psenner, A.: The evolutive meshed compact city – a new framework for the 15mC in peripheral areas. In: Proceedings of ECTQG2023, Braga, pp. 85–87 (2023). https://ucpages.uc.pt/site/assets/files/1249198/ectqg_2023_proceedings_final.pdf

Hillier, B., Penn, A., Hanson, J., Grajewski, T., Xu, J.: Natural movement: or, configuration and attraction in urban pedestrian movement. Environ. Plann. B. Plann. Des. **20**, 29–66 (1993)

Hillier, B.: Space is the Machine. Cambridge University Press, Cambridge (1996)

IGN: BD TOPO® Version 3.3, Descriptif de contenu. Institut national de l'information géographique et forestière, 387 p. (2023)

Kuhn, M.: Package 'caret': classification and Regression Training (Version 6.0–94) [Software] (2023). https://github.com/topepo/caret/

Lagesse, C.: Lire les Lignes de la Ville : Méthodologie de caractérisation des graphes spatiaux. Géographie. Université Paris Diderot-Paris VII, Thèse, 566 p. (2015)

Léger, J.-F.: Le lien logement-population à l'échelle locale. I – Le « rendement démographique » des logements. Espace populations sociétés, 2019/3 (2019)

Murgante, B., Valluzzi, R., Annunziate, A.: Developing a 15-minute city: evaluating urban quality using configurational analysis. The case study of Terni and Matera, Italy. Appl. Geogr. **162** (2024)

Perez, J., Fusco, G., Sadahiro, Y.: Population and morphological change: a study of building type replacements in the Osaka-Kobe City-Region in Japan. Geograph. Anal. , Early View, Online Version of Record before inclusion in an issue (2024)

Porta, S., Crucitti, P., Latora, V.: The network analysis of urban streets: a dual approach. Physica A **369**(2), 853–866 (2006)

Stavroulaki, I., Marcus, L., Berghauser Pont, M., Carl Staffan Nilsson, L.: Representations of street networks in space syntax towards flexible maps and multiple graphs. In: 11th International Space Syntax Symposium. SSS 2017, Lisbon, Portugal, 3–7 July 2017, vol. 5, pp. 174.1–174.16 (2017)

Steadman, P.: Building Types and Built Forms. Troubador Publishing Ltd., Leicestershire (2014)

The Spatial Roots of Urban Growth: Modelling Urban Dynamics with Space Syntax

Federico Mara(✉), Chiara Anselmi, Federica Deri, and Valerio Cutini

Department of Energy, Systems, Territory and Construction Engineering, University of Pisa, Largo Lucio Lazzarino, 56122 Pisa, Italy
federico.mara@phd.unipi.it

Abstract. The intricate interplay among urban sub-systems poses significant challenges in comprehensively interpreting urban dynamics and assessing the efficacy of urban planning strategies. Spatial modelling stands out as a crucial tool for analysis and decision-making in this context. This paper investigates the potential of Space Syntax in extracting intrinsic characteristics vital for understanding urban growth dynamics and spatial phenomena. Specifically, the study explores the inherently multiscale nature of Space Syntax, which offers a diverse array of techniques and measures for analysing urban systems, spanning from regional to architectural scales. In particular, the investigation focuses on the capability of Space Syntax to estimate vehicular and pedestrian flows and their correlation with the distribution of commercial activities, both at urban and neighbourhood scales, with a specific emphasis on the case study of Pisa, Italy, leveraging *Angular Segment Analysis*. In addition to the analytical exploration, the paper provides a concise historical overview, highlighting the transformations and peculiarities of Pisa's current urban form. The findings underscore the potential of the proposed methodology and Space Syntax multiscale approach for analysing urban settlements. Notably, the research reveals a correlation between heavily traversed streets and the localisation of commercial activities. These insights contribute to a deeper understanding of urban dynamics and offer valuable implications for urban planning and design.

Keywords: Spatial Modelling · Space Syntax · Multiscalarity · Urban Dynamics · Vehicular Flow · Pedestrian Flow

1 Introduction

The United Nations, through the Sustainable Development Goals (SDGs), has established the key objectives to be achieved in order to create sustainable and liveable urban environments. In particular, urban planning plays a crucial role in achieving SDG 11: Sustainable Cities and Communities, while also being closely interconnected with all other SDGs. However, pinpointing the precise mechanisms regulating different urban phenomena is highly complex. These are in fact the results of intricate interactions among the subsystems comprising city systems [1], which are inherently complex and interconnected organisms in continuous growth.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 61–76, 2024.
https://doi.org/10.1007/978-3-031-65238-7_5

In the quest to understand the short and long-term impacts of urban policies and interventions, or to evaluate alternative design scenarios, spatial modelling and digital twins play a central role [2]. In particular, models capable of simulating human behaviour and movement in cities are essential, serving as valuable decision support systems. Unlike Mara and Cutini [3], who highlighted the dichotomy of top-down and bottom-up tools in addressing modelling issues, this paper aims to closely analyse the theme of multiscalarity in configurational approaches, highlighting its natural predisposition, capabilities, and importance in urban planning.

Indeed, Space Syntax, both a theory and a set of analyses and measures capable of interpreting the urban networks hierarchy and extracting intrinsic spatial characteristics, is inherently multiscalar. Space Syntax modelling can be applied across various scales of analysis – from the regional to the architectural one – while maintaining its effectiveness [4]; it offers a wide array of analyses to choose from based on the scale of analysis and specific modelling requirements; it allows qualitative interpretation but also quantitative analysis (due to its analytical framework based on graph theory) of urban phenomena related to movement and the resulting social dynamics [5].

Moreover, the configurational approach has fundamentally overturned the spatial interaction model by revaluating the importance of urban form. While initially space was considered a scenic backdrop just marginally influential for urban dynamics, with the configurational approach, urban form becomes the protagonist of urban scenarios, capable of determining urban flows and consequently land use [6, 7] (see Fig. 1). Only through topological-visual and positional analysis of the various elements composing the urban environment is it possible to determine *a priori* the preferred vehicular and pedestrian movement pathways [7, 8], and simultaneously, the land use distribution [7, 9] of the urban environment.

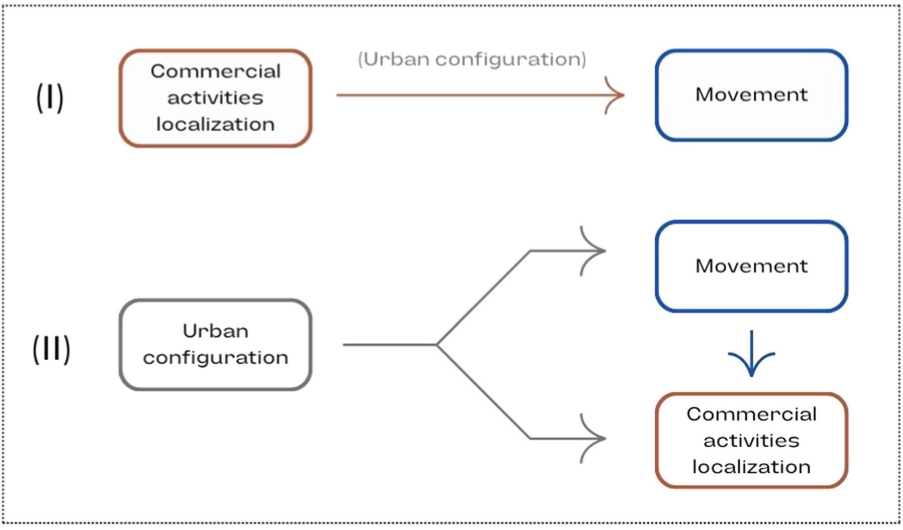


Fig. 1. Interactional (I) vs configurational (II) approach to urban planning.

In this perspective, this paper demonstrates the utility of the configurational approach at both urban and neighbourhood scales, highlighting the hierarchical logic of the historic urban settlement of Pisa, estimating the hierarchy of vehicular and pedestrian flows, and showing the correlation between centrality and the natural positioning of activities.

The paper is structured as follows: in Sect. 2, the case study and methodology are presented, describing the datasets and measures employed both for configurational analysis and for the extraction of commercial activities. Section 3 is divided into three parts: it first presents the study at the urban scale (Sect. 3.1), briefly tracing historical evolution, analysing the distribution of vehicular and pedestrian traffic, and discussing the correlation between flows and commercial activities distribution. Subsequently, it presents the same study at the neighbourhood scale (Sect. 3.2). Section 3.3 briefly discusses the results and highlight some aspects to be further explored. Finally, Sect. 4 summarizes the main findings.

2 Concepts, Datasets and Methods

2.1 Case Study

The historical city centre of Pisa, located in Italy's Tuscany region (Fig. 2), have been selected for this case study. Specifically, the area comprising the historic centre within the medieval walls, along with the adjacent neighbourhood extending towards the central train station (Fig. 3). According to this framework, a total of 5 neighbourhoods can be identified: *Santa Maria*, *San Francesco*, *Sant'Antonio*, *San Martino*, and the *Stazione* neighbourhood. For the neighbourhood-scale analysis, Santa Maria has been selected.

The city of Pisa is characterized by two distinctive features: it is a diffuse university city characterized by university facilities diffused all over the historical nucleus and a high number of students. Simultaneously, it is a tourist hub, primarily due to the historical landmark of *Piazza dei Miracoli*, the presence of the international airport

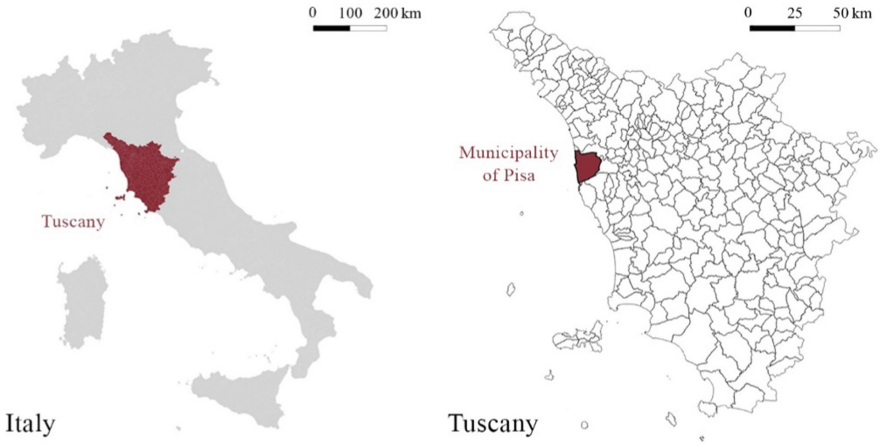


Fig. 2. Localization of Tuscany and Municipality of Pisa.

of the Tuscany region, and its proximity to Florence. This attractiveness results in the historical core being marked by a high concentration of dining commercial activities. Furthermore, because of the historical nature of the urban settlement, the central area is predominantly pedestrian and characterized by restricted traffic zones.

2.2 Datasets and Methodology

To conduct this study, three datasets were utilized. The spatial modelling of the urban grid (Road Centre Line) was achieved using data from Open Street Map [11]. The urban and neighbourhood grid was created with data provided by Geoscopio Toscana [12], from which the urban base map (Regional Technical Map 2K) was also extracted. The



Fig. 3. Pisa historical centre. Districts subdivision and landmarks

modelling of activities within the area was conducted by extracting functions' locations from the Open Street Map [9] geodata repository, then modelled using the QGIS suite [13].

From a methodological perspective, the study comprised three successive steps. Firstly, a historical-evolutionary analysis of the urban settlement through a semi-systematic bibliographic analysis [14] was conducted. This entailed tracing the transformations that the historic centre has undergone since the Middle Ages (10th century), considering the major changes in the built environment and the evolving use of urban spaces over the centuries.

Subsequently, spatial analyses were conducted at both levels. Drawing from Turner's studies [9], the Road Centre Line (RCL) was chosen as the base map for conducting Angular Segment Analysis to estimate both vehicular and pedestrian flow hierarchies at urban and neighbourhood scales. Specifically, the network was extended by 200 and 50 m respectively at urban and neighbourhood scale to mitigate edge effects. The measure adopted for flow analysis was the Normalized Angular Choice (Betweenness), considered its high correlation with vehicular and pedestrian flows [9, 10].

Concurrently, the functions within the study area were extracted from OpenStreetMap and categorized following the classification by Pezzica et al. [15]. Both point and polygon data were taken into account, by merging them into a single point layer. Unclassified data weren't considered. Therefore, a qualitative and quantitative evaluation of commercial activities distribution in relation to the centrality values of network segments was done. Specifically, regarding the quantitative analysis, activities were associated with the road on which they are located, and the percentage of activities located on network segments with the highest NACH values (10, 20, 30%) was calculated both at the urban and local scales.

3 Results and Discussion

3.1 Urban Scale Analysis

Historical Analysis. During the 10th century, the historical centre of Pisa was enclosed within a very small circle of walls. The first expansion occurred around the year 1000, dividing the city into four main districts: "Ponte" in today's Santa Maria neighbourhood, "Mezzo" further north, "Foriporta" (San Francesco), and "Chinzica" south of the Arno River. The current configuration of the city walls was established around 1150 by the consul Cocco Griffi, incorporating the borough area, the Cathedral Square, and Chinzica [16].

From the Late Middle Ages (11th century) onward, Pisa declined under Florentine dominance, with the city confined to the Santa Maria neighbourhood. An economic and demographic recovery began in the 16th century, marked by numerous architectural and artistic endeavours, land reclamation works throughout the countryside, and the restoration of Pisa's *terziario*, namely the transformation of the city in a commercial hub, an artisanal and mercantile centre, as well as a noble and university town under the governance of Cosimo de' Medici. Notable constructions during this period include *Piazza dei Cavalieri*, *la Sapienza*, which was the main university hub, *Piazza delle Vettovaglie*, la *Loggia dei Mercanti*, *l'Arsenale della Cittadella Vecchia*, l'*Orto Botanico* (please refer

to Fig. 3); the *Lungarni* flourished with the construction of several aristocratic palaces, becoming the most prestigious streets of the era. The most densely populated residential area remained the Santa Maria district, which retained its commercial nature [17].

Unlike other Tuscan cities, Pisa has historically comprised several economically and socially significant nuclei without a true central core. The city's heart shifted over the centuries from *Piazza dell'Arcivescovado* in Roman times to *Piazza della Pescheria* in the early Middle Ages (now *Piazza delle Vettovaglie*), and then to *Piazza dei Cavalieri* during *Medici* rule. Some scholars argue that the city has experienced a shift away from the traditional squares towards the *Borghi-Corso Italia* axis [17]; *Piazza Santa Caterina*, for example, is located in a central position, but actually marginal in the city's community life. Pisa's ancient road network is a mixture of narrow, winding medieval streets and a grid echoing the 19th century patterns [18], with frequent intersections between narrow and wide streets: a main road crossing the Arno River (today's *Corso Italia* and *Borgo*) and others parallel to it, connecting to the city gates, interlinked by alleys.

In the 19th century, there was a surge in public works focusing on demolition and saturation to introduce new roads, occupying most of the green areas within the walls. The limits of Cocco Griffi's walls were exceeded in the post-war period, creating a series of radial nuclei around the medieval city. Urban development, however, witnessed disorderly growth, characterized by rampant construction speculation, in particular along Lungarno Mediceo, and saturation of areas adjacent to the walls. Over the years, the university continued to expand, facing challenges in introducing new campuses and coexisting with the local population, who have been displaced by the conversion of residences into student apartments.

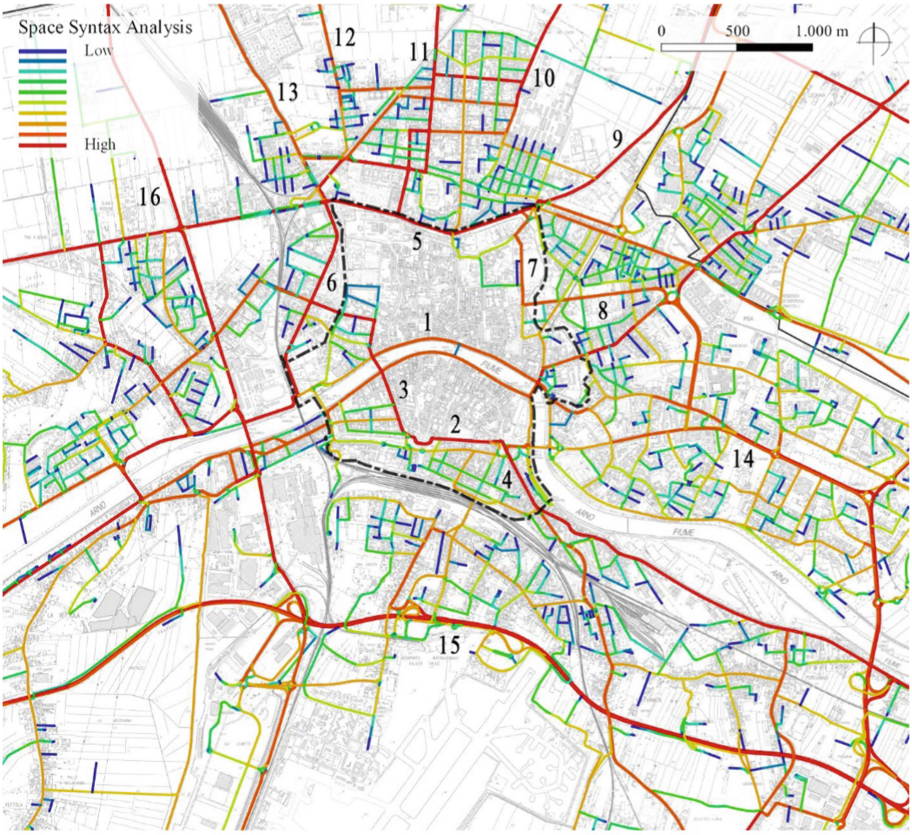
Vehicular Flow Analysis. The inter-municipal road network, comprising the municipality of Pisa and adjacent municipalities, was analysed to highlight the traffic roads in the suburb of Pisa as well as in the historical center, largely characterized by Limited Traffic Zones, excluded from the analysis. The ASA RCL (NACH Rn) (Fig. 4) shows two main axes crossing the historical centre, *Lungarni* and an axis near the ancient walls in the South, *Via Benedetto Croce*, (separating the station district from *San Martino*), which continues westward to *Via Crispi-Ponte Solferino-Via Roma-Via Risorgimento* and eastward to *Via Cattaneo*, then *Via Fiorentina* and *Via Emilia.* From the outside, vehicular flows distribute along the walls to the north (*Via Contessa Matilde*), reconnecting to the *Lungarni* via *Via Bonanno Pisano* to the west and crossing the walls through *Via Buonarroti* and *Via San Francesco*/*Via San G. Bosco* to the East. Moreover, among the main axes departing from the center emerges *Via del Brennero* to Lucca, then *Via di Gello*, *Via XXIV Maggio*, *Via San Jacopo* and *Via Pietrasantina* to the north, and *Via Matteotti*/*Matteucci* leading to *Cisanello* to the east. Among the main suburban axes, becomes evident either the Fi-Pi-Li highway in the southern area, or the Aurelia state road running vertically in the western area. The ASA RCL analysis proves the city of Pisa to be an attractive/diffusing hub in all directions, characterized by radial axes with NACH high values, from the historical center to the many adjacent nuclei.

Pedestrian Flow Analysis. The ASA RCL (NACH Rn) calculated on the historical centre road network, highlights the preferred pedestrian routes (Fig. 5). Particularly, the hierarchy reveals several aspects emphasized in the historical-evolutionary reconstruction. The presence of a single preferential vertical axis that continuously traverses

the entire centre from south to north (*Corso Italia-Ponte di Mezzo-Borgo*), supports the shift in centrality from squares to the central urban axis described by [17]. However, additional vertical axes characterized by significant centrality emerge. In the southern portion, *Via Sant'Antonio* emerges, while in the northern portion, from west to east, *Via Roma*, *Via Santa Maria*, and *Via Buonarroti* (please refer to Fig. 5) come out. As the main transversal axes, *Via Battisti - Viale Bonaini*, the two *Lungarni*, and the axis *Via Contessa Matilde - Via del Brennero* arise – this last one despite its marginality in the system, as it was constructed. Then, a series of transversal segments connecting these primary axes to the surrounding areas, emerge: *Via Cottolengo-Manzoni*, *Via Turati*, *Via San Martino*, *Via Giusti-Palestro*, *Via San Francesco*, *Via San Lorenzo*, and *Via Pietro Maffi*.

Curiously, all the paths that identify the boundary between adjacent neighbourhoods are configurationally strong, echoing Lynch's analysis [19], according to whom paths can represent boundaries of urban tissue, and thus act as elements of segregation between adjacent neighbourhoods. The axis *Corso Italia-Borgo*, the *Lungarni*, and, to the south – with a slight shift from the actual 'boundary' between the Stazione and Sant'Antonio and San Martino neighbourhoods – the transversal axis *Via Battisti-Viale Bonaini*, are clear examples of this concept. Also noteworthy is the presence, among the 20% of the most integrated axes, of the streets that give their names to the 4 historical neighbourhoods: *Sant'Antonio* and *Santa Maria* are the vertical ones, *San Martino* and *San Francesco* are the transversal ones. Moreover, *Piazza dei Miracoli*, despite being in a position far from central, is naturally characterized by pedestrian flow.

Commercial Activities Distribution. After assessing the hierarchy of the road network, the distribution of commercial activities was analysed. As outlined in Sect. 2, functions were extracted from OSM and categorized into the 6 macro-categories highlighted in Table 1. Specifically, to examine the spontaneous distribution of commercial activities, the macro categories of commerce and entertainment (in red) were considered (Fig. 6). In the background, only the road network categorized according to Urban ASA RCL measures (NACH Rn) in 10 classes is represented. A preliminary qualitative analysis reveals that a significant portion of commercial functions is distributed along the central axis of *Corso Italia-Borgo*, with a more substantial presence of commercial functions in the northern portion compared to the southern portion of Pisa, thus reflecting the area's historical commercial prominence. However, a basic quantitative analysis was conducted to assess potential correlations between commercial activities distribution and pedestrian flows. Specifically, the number of activities located in high-betweenness streets, and therefore characterized by great through-movement potential, was examined. In particular, the number of commercial activities located in the top 10, 20, and 30% of streets with the highest NACH values was calculated (see Table 2). It emerged that 30% of the commercial activities in the historic centre are concentrated on streets with the highest 10% NACH values, and furthermore, 60% of the activities concentrate on streets with the highest 20% NACH values. Remarkably, almost 70% of the activities concentrate on streets with the highest 30% NACH values. This proves the configurational logic, wherein the urban network determines areas of greater centrality and high flows, thus attracting commercial activities localization and confirming Hillier's theory [20] (please refer to Fig. 5).



MAIN AXES

1 Lungarni	7 Via Buonarroti	13 Via Pietrasantina
2 Via Benedetto Croce	8 Via San Francesco-Via San G. Bosco	14 Via Matteotti-Via Matteucci
3 Via Crispi	9 Via del Brennero	15 Fi-Pi-Li highway
4 Via Cattaneo	10 Via di Gello	16 Via Aurelia
5 Via Contessa Matilde	11 Via XXIV Maggio	
6 Via Bonanno Pisano	12 Via San Jacopo	

Fig. 4. Municipality RCL Angular Segment Analysis, NACH Rn (Equal Count). Analysis of the vehicular flow through the urban and periurban areas.

3.2 Neighbourhood Scale Analysis: Santa Maria

Historical Analysis. The Santa Maria neighbourhood encompasses the ancient city area within the first wall. Throughout the history of the city, it always held a significant role. It hosts *Piazza dei Cavalieri* (please refer to Fig. 3), which in Roman times represented the city centre, hosting the forum of the Republic, and during the communal era was the site of the traditional *Gioco della Mazza Scudo* – named *Gioco del Ponte* after its relocation over *Ponte di Mezzo* [21]. It is also remembered for the tower of the Dantean Count Ugolino in the Gherardesca palace. The new layout of the square, however, dates back

Table 1. Categorization of activities extracted by Open Street Map (OSM) repository. In bold the functions selected for the investigation.

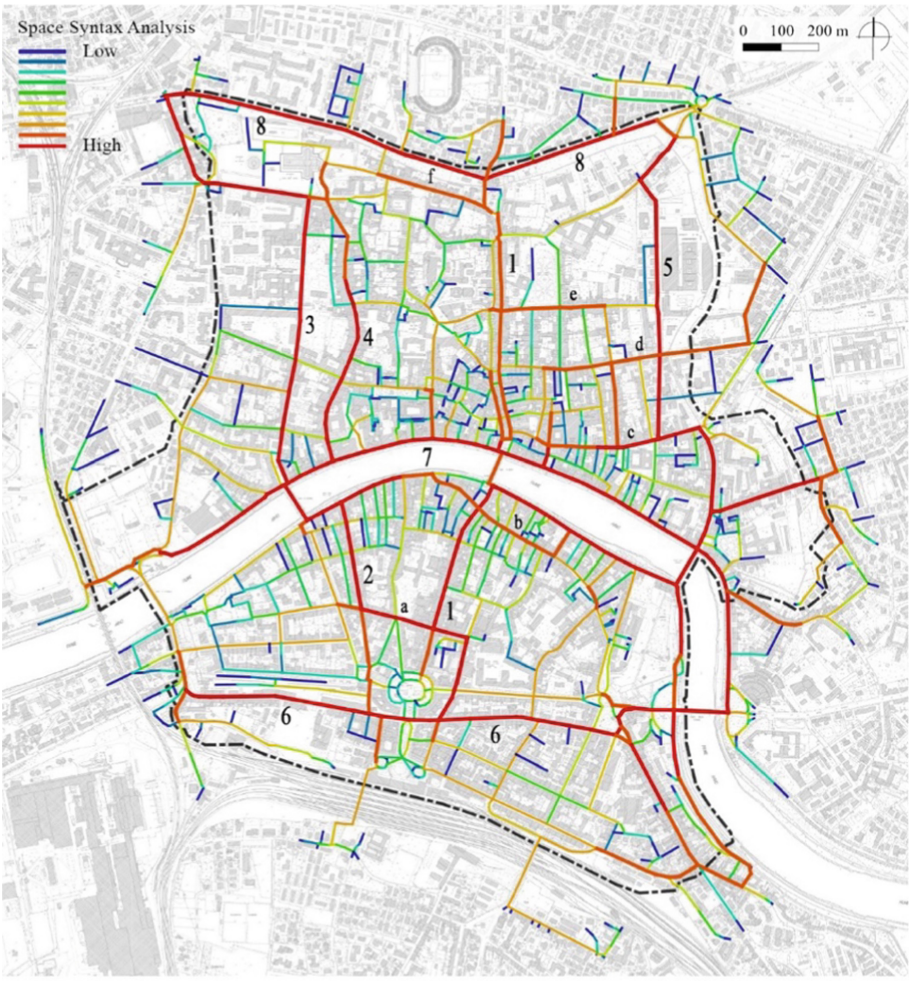
Function	Key	OSMCategorization
Commerce	**Shop**	**Shop**
	Amenity	**Sustenance**
	Amenity	**Financial**
Healthcare	Amenity	Healthcare
Education	Amenity	Education
Entertainment	**Amenity**	**Entertainment, arts & culture**
Other services	Amenity	Public Service
		Facilities
		Waste Menagement
Transportation	Amenity	Transportation

Table 2. Quantitative analysis: correlation between NACH and commercial activities distribution.

% NACH	OSM Commerce		% OSM
	Total	% NACH	
10	853	268	31
20	853	509	60
30	853	585	69

to the mid-19th century. Already in the 11th century, the neighbourhood's location had strong urbanistic importance in relation to the monumental *Piazza dei Miracoli*, hosting the Cathedral, the Baptistery, the Bell Tower, and the Cemetery, built after the inclusion of the area within the city walls. Moreover, the neighbourhood included the *Sapienza* building, the *Rossi* Theatre, the Botanical Garden, the Archbishop's Palace [21]. *Piazza delle Vettovaglie* represents another key element of the neighbourhood, built between 1494 and 1553 after the excavation of a part of Pisa's ancient nucleus in order to establish the market there; it has always maintained its commercial vocation, formerly home to numerous butcher shops and now to the roaming fruit and vegetable market, as well as the vital centre of Pisa's evening entertainment scene.

The Santa Maria neighbourhood appears heterogeneous, historically characterized by high population density, with buildings prevailing over the green areas. The area was further densified, like many others in the historic centre, between the 17th and 18th centuries. In particular, the Vettovaglie area and the area adjacent to the western walls were densified in consequence of the Solferino bridge construction (1875) which directly connected Santa Maria to Sant'Antonio [16].



MAIN VERTICAL AXES	MAIN TRANSVERSAL AXES	SECONDARY TRANSVERSAL AXES
1 Corso Italia-Borgo	6 Via Battisti-Viale Bonaini	a Via Cottolengo-Manzoni
2 Via Sant'Antonio	7 Lungarni	b Via San Martino
3 Via Roma	8 Via Contessa Matilde-del Brennero	c Via Giusti-Palestro
4 Via Santa Maria		d Via San Francesco
5 Via Buonarroti		e Via San Lorenzo
		f Via Pietro Maffi

Fig. 5. Urban RCL Angular Segment Analysis: NACH Rn (Equal Count). Analysis of the pedestrian flow through the urban historical centre.

Pedestrian Flow Analysis. Analyses at the neighbourhood scale highlight more prominently the main local axes, which nevertheless confirm the hierarchy observed at the urban scale (Fig. 7). The axe of *Via Santa Maria* and *Via Roma* emerge, this last one maintaining high values despite the disconnection with the bridge and the southern area.



Fig. 6. Commercial activities distribution over the 10 classes equal count categorization of the urban RCL ASA (NACH Rn) network.

Additionally, despite their marginal position and the edge effects, the axis of Borgo to the east and Lungarno Pacinotti to the south arise. Compared to the urban scale, the axes leading to Piazza dei Cavalieri (*Via Consoli del Mare* and *Via San Frediano*) are more prominent, underscoring the centrality of this square. The dominant entrance across the walls from the outside seems to be in *Piazza del Duomo*, actually the main tourist hub, strongly predominant in comparison with the other parallel streets in the western area.

Commercial Activities Distribution. As for the historical center, the macro categories of commerce and entertainment (in red) were considered (please refer to Table 1) to show the distribution of commercial activities (Fig. 8). From a preliminary qualitative analysis, an activities' agglomeration is revealed in the south-eastern portion of the district, along

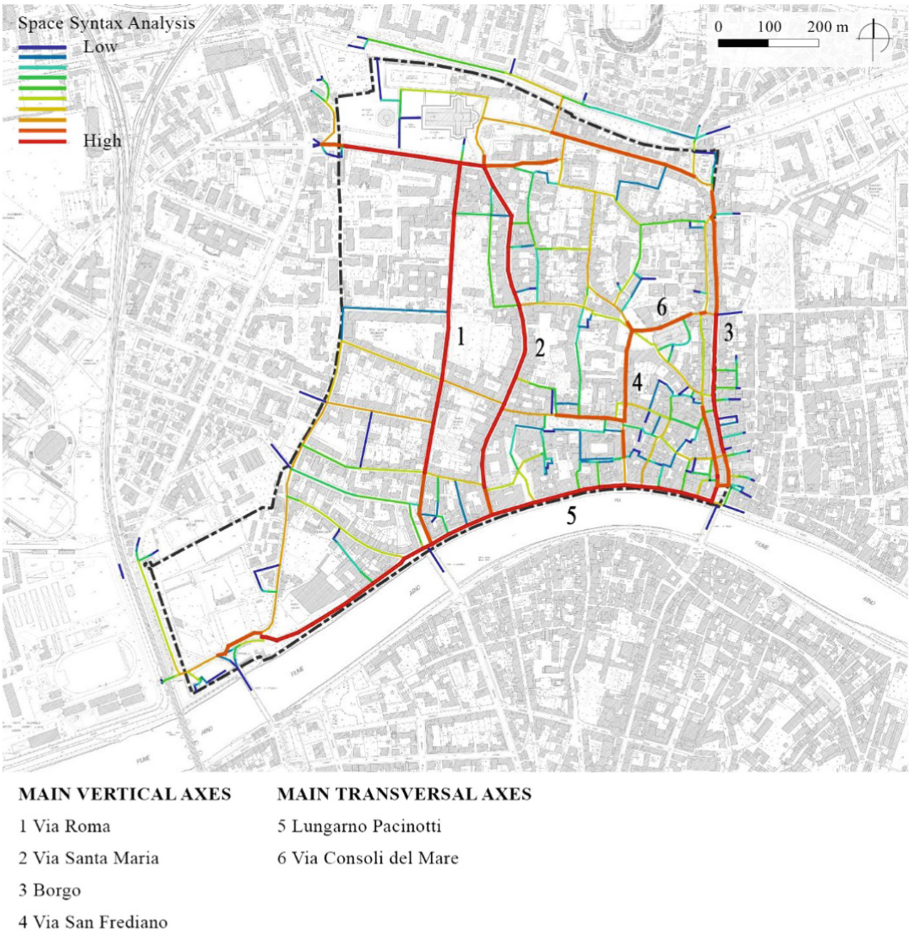


Fig. 7. Urban RCL Angular Segment Analysis: NACH Rn (Equal Count). Analysis of the pedestrian flow through the Santa Maria neighbourhood.

Borgo Stretto and the axis of *Via l'Arancio-Via Cavalca,* but is also displayed a concentration in the central area of *Via Santa Maria* and *Via dei Mille*, to *Piazza dei Cavalieri. Piazza delle Vettovaglie* confirms its historical commercial vocation. A basic quantitative analysis shows the potential correlations between the activities and the pedestrian flow in the road network, categorized according to Urban ASA RCL measures (NACH Rn) in 10 classes. Differently from the urban scale, there is a notable rise of the rate of the activities concentrates on the street with the highest NACH values, particularly within the top 10% NACH values where it reaches 45% (Table 3). There is no homogeneous concentration of activities on roads with higher NACH values; some of these axes, in fact, host a small number of commercial activities (e.g., *Via Roma*).



Fig. 8. Commercial activities distribution over the 10 classes equal count categorization of the neighbourhood RCL ASA (NACH Rn) network.

Table 3. Quantitative analysis: correlation between NACH and commercial activities distribution.

% NACH	OSM Commerce		% OSM
	Total	% NACH	
10	329	149	45
20	329	222	67
30	329	241	73

3.3 Urban vs Neighbourhood Scale: A Brief Comparison

The multiscalar analysis has proven useful in investigating various aspects, despite the slight dimensional difference between the two systems, with Santa Maria being approximately a quarter of the historical centre of Pisa. Firstly, the RCL ASA NACH analysis at the inter-municipal scale – performed after eliminating the area forbidden to vehicular flow from the system – highlighted the vehicular movement patterns [9]. The same measure, calculated on the complete urban system and referred to as 'urban RCL', has highlighted pedestrian preference routes instead. This analysis has essentially shown

how the major flows concentrate on the axes separating historical neighbourhoods and in the ancient cores of each neighbourhood, providing the input to further explore this correlation, which could prove useful in intercepting the primary historical axes of historical cities. A similar analysis has been developed at the neighbourhood scale in the Santa Maria neighbourhood, where the logic identified at the urban scale was confirmed but supplemented by the to-movement potential represented by Piazza dei Cavalieri and the streets leading to it.

Examining the second-order indices [7], further peculiarities of urban settlement are highlighted. Second-order indices derive from primary configurational indices and are capable of describing the configurational characteristics of the entire system rather than just its individual elements, thus proving to be significant indicators of the overall characteristics of the analysed settlement. Specifically, the Synergy index – a correlation index R^2 between global integration index and local integration index – reveals how the local relational and spatial organization of the settlement is well grounded in its global organization, both at the urban scale ($R^2 = 0.73$) and even more so at the neighbourhood scale ($R^2 = 0.81$), indicating coherent spatial relationships across various scales. Indeed, where the strong global integrators are also strong local integrators, it means that the network of dominant relationships within portions of the settlement coherently ties into the network of spatial relationships of the entire system [7]. Conversely, both the urban and the neighbourhood systems are characterized by a low Intelligibility index – a correlation index R^2 between global integration index and connectivity index –, thus indicating a weak correlation between the global integration index and the connectivity index. Essentially, the two systems are not easily interpretable by an external visitor, who will have difficulty orienting themselves in the urban grid due to the lack of correspondence between integration and the number of prospective connections. Indeed, where the main hubs do not correspond to a high number of visual openings onto adjacent paths, orientation for a visitor will be more difficult compared to the opposite situation where main hubs correspond to a high number of connections on nearby paths. Nevertheless, the network of Santa Maria neighbourhood emerges as more easily understandable ($R^2 = 0.46$) than the historical centre ($R^2 = 0.33$) Table 4.

Table 4. Sinergy index and Intelligibility index of the urban and neighbourhood systems.

Second order indices	Urban scale [R^2]	Neighbourhood scale [R^2]
Sinergy value	0.73	0.81
Intelligibility value	0.33	0.46

Furthermore, on both scales, RCL NACH has demonstrated a strong correlation with the distribution of commercial activities, indicating a significant clustering of these businesses along streets characterized by high-NACH values.

Several potential improvements to the methodology have been identified. Particularly, it would be valuable to assess the differences between the use of RCL ASA, isovist-based ASA, and Visibility Graph Analysis (VGA) in both estimating flows and

exploring correlations with the distribution of activities. However, in the case of line-based analysis and VGA, a more refined methodology would be necessary to accurately associate commercial activity's location with isovists, considering the increased segmentation/granularity of those analysis. Additionally, for neighbourhood analysis or any micro-scale analysis, conducting on-field verification of OSM data concerning the existence and location of commercial activities may be necessary to improve the accuracy of the research. Finally, further quantitative analysis methodologies could be tested.

4 Concluding Remarks

This study highlighted the natural ability of the configurational approach to interpret urban dynamics across multiple scales. More than this, Space Syntax has proven capable of interpreting the spatial roots of urban growth by intercepting dynamics that, by their very nature, develop at different scales, contingent upon distinct sub-systems. Specifically, it has been demonstrated the capability of the Space Syntax technique to interpret vehicular and pedestrian movement at the urban and neighbourhood scales, as well as to illustrate how the natural distribution of commercial activities in the territory follows configurational logics. Moreover, given the analytical framework of this approach, it is possible to combine qualitative analyses of network hierarchy with quantitative analyses that, using appropriate techniques, allow for comparisons between different urban grids.

Future studies should work in two directions. On one hand, to deepen the multiscale potential of the configurational approach, evaluating the various information that can be extracted from the urban network from the regional scale to the micro-urban scale, through the testing of various metrics and analysis techniques: Axial Analysis, Angular Segment Analysis, Visibility Graph Analysis. On the other hand, test the effectiveness of Space Syntax in investigating sub-systems related to urban dynamics that it is able to detect, such as the investigation of the location of commercial activities, the functioning logics of multimodal transportation, criminal dynamics, and urban sprawl phenomena, still through a multiscale and multi-techniques comparative approach.

References

1. Crooks, A., Malleson, N., Malleson, N., Manley, E., Heppenstall, A.: Agent-based modelling and geographical information systems: a practical primer. Sage (2018)
2. Wan, L., Nochta, T., Tang, J., Schooling, J.: Digital Twins for Smart Cities: Conceptualisation, challenges and practices. ICE Publishing (2023)
3. Mara, F., Cutini, V.: Space syntax vs agent-based modelling in the maze of urban complexity: a critical comparison between top-down and bottom-up approaches and applications. In: Marucci, A., Zullo, F., Fiorini, L., Saganeiti, L. (eds.) Innovation in Urban and Regional Planning. INPUT 2023. Lecture Notes in Civil Engineering, vol. 467. Springer, Cham (2024). https://doi.org/10.1007/978-3-031-54118-6_52
4. Yamu, C., Van Nes, A., Garau, C.: Bill Hillier's legacy: space syntax—a synopsis of basic concepts, measures, and empirical application. Sustainability **13**(6), 3394 (2021)
5. Van Nes, A., Yamu, C.: Introduction to Space Syntax in Urban Studies. Springer Nature (2021).https://doi.org/10.1007/978-3-030-59140-3

6. Cutini, V.: La rivincita dello spazio urbano. L'approccio Configurazionale Allo Studio e All'analisi Dei Centri Abitati (2010)
7. Cutini, V.: La forma del disordine: Tecniche di analisi e progetto urbano ai tempi dello sprawl, pp. 1–226. Mimesis Edizioni (2016)
8. Hillier, B., Penn, A., Hanson, J., Grajewski, T., Xu, J.: Natural movement: or, configuration and attraction in urban pedestrian movement. Environ. Plann. B. Plann. Des. **20**(1), 29–66 (1993)
9. Turner, A.: From axial to road-centre lines: a new representation for space syntax and a new model of route choice for transport network analysis. Environ. Plann. B. Plann. Des. **34**(3), 539–555 (2007)
10. Hillier, B., Iida, S.: Network and Psychological Effects in Urban Movement. In: Cohn, A.G., Mark, D.M. (eds.) Spatial Information Theory, pp. 475–490. Springer Berlin Heidelberg, Berlin, Heidelberg (2005). https://doi.org/10.1007/11556114_30
11. OSM. OpenStreetMap. https://www.openstreetmap.org/#map=6/54.910/-3.432. (2024)
12. Regione Toscana.: Direzione Urbanistica e Politiche Abitative - Sistema Informativo Territoriale e Ambientale – SITA: Grafo stradario e ferroviario della Regione Toscana (2019)
13. QGIS, Firenze version 3.28 LTR, http://www.qgis.org/en/site/index.html.(2022)
14. Snyder, H.: Literature review as a research methodology: an overview and guidelines. J. Bus. Res. **104**, 333–339 (2019)
15. Pezzica, C., Altafini, D., Mara, F., Chioni, C.: Travel-time in a grid: modelling movement dynamics in the "minute City". In: Marucci, A., Zullo, F., Fiorini, L., Saganeiti, L. (eds.) Innovation in Urban and Regional Planning. INPUT 2023. Lecture Notes in Civil Engineering, vol. 467. Springer, Cham (2024). https://doi.org/10.1007/978-3-031-54118-6_58
16. Tolaini, E.: Forma Pisarum. Storia urbanistica della città di Pisa – problemi e ricerche. Nistri-Lischi Editori (2013)
17. Masetti, A.R.: Pisa. Storia Urbana. Piante e vedute dalle origini al secolo XX. La Giuntina, Firenze (1964)
18. Frattarelli Fischer, L., Nucara Dani, C.: Il quartiere di San Francesco. Progetti e interventi ottocenteschi su una zona medievale di Pisa. Tacchi Editore, Pisa (1989)
19. Lynch, K.: The Image of the City. MIT press (1964)
20. Hillier, B.: Space is the Machine. Cambridge University Press, Cambridge (1996)
21. Vallerini, A.: Nuova Guida di Pisa. Terza Edizione. Editore Pisa (1932)

Public Participation in the 15-Minute City. The Role of ICT and Accessibility to Reduce Social Conflicts

Beniamino Murgante[1] and Irina Di Ruocco[2(✉)]

[1] School of Engineering, University of Basilicata, Viale dell'Ateneo Lucano 10, 85100 Potenza, Italy

[2] University of Insubria, DIECO, Via Monte Generoso 71, 21100 Varese, Italy

idiruocco@uninsubria.it

Abstract. The 15-minute city is a well-known concept and widely analysed in academic research. Experiments have often taken place with top-down pilot cases, often without citizen involvement.

Experiences show that the 15-minute city has given rise to some syndromes, which leads us to reflect on how to realise an accessible city by incorporating participation and limiting oppositional phenomena. To support this, digital smart governance tools, such as e-democracy and e-participation, aim to provide citizens with information services, listening channels and promote their participation in public life and urban processes.

This research aims to analyse the 15-minute city in its critical aspects that have emerged in the literature, assessing whether it is a correct model in its approaches and what relationship exists between participation in public life, ICT and the 15-minute city. The study analyses the Italian national context to identify the relationship between accessibility, job satisfaction, and public participation, to understand whether the living conditions of citizens and the proximity and accessibility of places are linked to the emergence of syndromes. The objective is to identify possible relationships, to understand what happens in daily life that could lead to the emergence of syndromes, and to suggest practical measures based on the evidence from this survey.

Keywords: 15-min city · conflicts · participation

1 Introduction

Many urban planning measures introduced in recent years with the aim of reducing emissions, having greater inclusiveness in urban processes, and adapting urban planning to the needs of cities, have shown a phenomenon of opposition and mistrust towards measures to make cities eco-friendly, such as the creation of the 15-minute city. Such opposition is evident both from a scientific point of view, with the investigation of some scholars, and at the level of public debate. The '15-minute city' or 'x-minute city' as an urban planning theory aims to make neighbourhoods more liveable and walkable.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 77–92, 2024.
https://doi.org/10.1007/978-3-031-65238-7_6

Recently, conspiracy theorists around the world have branded this idea a secret scheme to take cars away from people and trap residents in 'ghettos' [1–3]. Some studies, in addition to finding the advantages of the 15-minute city, have analysed the cost-effectiveness and which indicators are crucial for the urbanist process. How-ever, downstream of the empirical evidence, the 15-minute city has become an instrument of conspiracy against motorists, or a model of segregation, in which there is no inclusiveness, but only reduction to closed neighbourhoods, could exacerbate inequality [3, 4], pointing out whether the 15-minute city oscillates between dystopia and utopia, contributing to conspiracy theory [5, 6]. Recent protests in cities such as Oxford (UK), Edmonton (Canada), or Madrid have been characterized by a variety of claims and objections about the 15-minute city model [7, 8]. Main criticisms towards 15-minute city policies include social engineering fears, dis-trust of centralized urbanism, automotive freedom concerns, and environmental and gentrification risk [1, 9].

The 15-minute city initially considered, presented itself as an innovative but also inclusive approach with a view to more resilient and smarter cities, topics much debated in the literature. According to Vinod Kumar [10–14], it is posited to consider up to six components of a smart city such as smart people, smart economy, smart mobility, smart environment, smart living, and smart government.

According to the author, any city has the potential to become a smart city if it can develop from its current state and move towards these six smart city elements in an integrated and comprehensive manner. Regarding the smart government and living component, in car to urban planning are the increasingly refined and wide-spread Information and communications technology "ICT", including the possibility of real-time indicators, big-data, up to Internet of Thing "IoT". Precisely to make urban measures more fluid, the Internet of Things can be used to govern the smart city as an ecosystem, but the management of the smart city as a socio-economic and cultural system would require more. Besides the IoT, two other systems are needed for a smart city: the governance network (e-Governance) and the Internet of People (also known as e-Democracy).

The right to the city has reverted to the 15-minute city, as they argue [16] its realisation requires social mix actions at the neighbourhood level, but these are insufficient to address the deeper structural issues that perpetuate spatial inequality and deprivation.

The link between the 15-minute city and e-democracy has not been fully analysed in the literature. Instead, concerns emerge about the nature of conflicts and revolts over the 15-minute city on a collective level, accusing the measure of not being inclusive and thus not improving citizen participation in the city. From the perspective of governance in urban processes Both the concept of e-democracy and e-participation are creating new opportunities and problems for involvement [17]. An incentive for democratic participation is provided by a strong system of e-democracy, also known as the Internet of People, which can ensure better policies for the community.

The existing research on e-participation has primarily focused on the technological solutions or implementation challenges, paying less attention to the role of e-participation in planning practice or the changes in the engagement processes. The studies tend to focus on the use of specific solutions, e.g. interactive websites, different geospatial solutions, planning support systems, mobile applications, or social networking sites. Few studies provide a comprehensive analysis of the planning context, participatory procedures, and

the use of digital solutions that support these processes [18]. This article analyses the phenomenon between e-democracy and participation in the context of conflicts emerging in the 15-minute city. Neighborhoods and cities are transformed through an inclusive approach using a range of techniques and tools for public involvement through participatory urban planning. The importance of neighborhoods is also demonstrated by many practical cases, e.g. [19] shows that the right of residents to oppose local projects and Swiss mechanisms of direct democracy strongly influence spatial development processes.

Through community co-creation and participatory planning, cities can uncover prospects that were previously untapped, particularly when it comes to tackling problems like traffic, overcrowding, challenging governance, and social segregation. Behind e-democracy as a structural framework, empirical and practical evidence on policy acceptance demonstrates the existence of influence for both socio-political reasons, which change social and political boundaries, but also for individual reasons, creating a link between behavioral theory, e-democracy and urban measures. Many of e-participation solutions are perceived or promoted as an answer to the existing challenges of participatory planning, e.g. increasing public participation [20]. Collaboration requires taking step further and establishing a partnership among different stakeholders for joint plan-making and decision-making [18]. This research answers the following research questions: "Is there a correlation be-tween accessibility and political participation?" and "Can satisfaction in life and work lead to having trust in the institutions, to accept the measures proposed by the City of 15 Minutes?" based on the current trend of participation, the need to think of the 15-minute city in political and implementation terms, as well as on the basis of the living conditions of citizens. The article is structured in this way. The Sect. 1 describes the introduction to the theme of digital democratic participation, the 15-minute city, and the problem of the 15 minute city with public participation, avoiding clashes and syndromes. In the Sect. 2 we present the literature in line with the research. The Sect. 3 presents the methodology and the applied dataset. In Sect. 4 results and finally in Sect. 5 the conclusions and recommendations.

2 Literature Review

The effects of the 15-minute city have been thoroughly examined by empirical research, from its initial implementation [21] to its most recent applications in the context of the resilient and smart city. The idea is to reduce traffic demand, total time spent in traffic, congestion, and pollution by providing people with access to all daily necessities and important services (health care, education, etc.) within X minutes of active transportation (bicycling, walking, etc.). It should be noted that Moreno's first vision for an X-minute city does not incorporate public transportation and instead emphasizes accessibility to essential services [22].

Local governments across the world have embraced smart city agendas to address pressing urban issues. Technology and participation have always been crucial, but their importance has increased with the adoption of the 2030 Agenda and other sustainable policies by many national and municipal governments [23]. As shown by [24], people are more inclined to accept a policy if they believe it addresses an issue that they are responsible for, especially if that group also carries the financial responsibility of finding a solution.

For the promotion of democracy and strong decision-making process, the public participation in urban planning also acts as a tool for gathering information. [24] refer to the "middleman paradox," which is consistent with other earlier studies showing that a relatively small percentage of e-democracy proposals make it past the formal political decision-making stage and move on to become significant e-government initiatives on national or international agendas. Citizens are the providers and users of local knowledge and skills, which are essential for urban planning, achieving political and economic objectives, and allocating scarce resources, in addition to the strategic knowledge held by businesses [25]. There exist variations to the argument that urban design is considering the 15-minute city, which is a community that has amenities within walking distance [26]. Many authors have analysed the role of democratic participation, such as [27–29] analysing how the internet improves awareness and spreads political news. [27] analysis reveals that the Internet has raised high expectations of vitalisation and change of political democracy. [29] examine e-participation in Norway at the local level to investigate how municipal size affects online involvement and to learn that while traditional offline participation predictors similarly affect online participation, youth activity is encouraged by the Internet. Digital technologies supporting governance have emerged more recently, and they show both the intricacy and the ease with which participatory processes can be facilitated analysing the relationship with the rights to participation and inclusion [30–32]. [33, 34] declared that e-democracy is now feasible due to the adoption of a technology-enabled citizen-local government cooperation plan to enhance sustainable development. According to [35], many believe that ICT-enabled participation presents a clear and practical path toward developing a conversation tool between local government and urban residents for the joint improvement of urban sustainability.

Participation, ICT use, and e-democracy are related if it is true that technology may facilitate involvement and that we all own smartphones these days [36].

Several instruments are being examined to increase engagement to comprehend how to organize integrated participation to lessen possible disputes on the fifteen-minute city. These include, as stated by [37], aiming for an inclusive democracy of doing that is based on political investment, participation, and communication; [38] proposing self-organization in urban development; and [39] and [40] strengthening the socioeconomic conditions and geographic distribution of the population.

ICT applications' potential to change people's mistrust of political representatives and their indifference to public issues is questioned by experts as well as practitioners [41]. Since the deployment of these tools restricts participation to those with access to digital devices, the use of ICTs also raises concerns about exclusion, frequently ignoring the diverse viewpoints of citizens when making decisions or soliciting feedback on ICT-enabled participation processes [41–43].

The public can provide government agencies with insightful recommendations that will enable them to make better policy decisions [23]. Relevant elements include: (1) the degree of interaction between different citizen involvement modes in urban governance; (2) the population's representativeness; and (3) the incentives for citizens to participate [45]. Although it has been extensively studied in the literature, the 15-minute city is still applicable in certain circumstances but not in others. Thus, urban plans stress how important it is to reorganize cities. The C40 cities initiative, which includes 100

major cities in numerous countries, highlights that the implementation of policies based on the 15-minute city concept is an essential precondition for an equitable and long-lasting pandemic recovery [45–47]. [48–51] have examined it in Europe with respect to sustainability, accessibility, and indicator measurement. In Italy, studies are being conducted to determine a measure for the 15-minute city [50] for medium-sized cities or for metropolitan cities [51–54].

3 Data and Methodology

The approach is based on econometric modelling of the variables that could lead to conflicts or discontent in the public domain. We consider the analysis of the 2021 "daily life survey" dataset provided by Italian National Dataset "ISTAT" with a total of 25,000 families for all the Italian territory [55].

For our case study, the final dataset collects from a total of 35 variables, divided into categories and analysing with an econometric model the relationship between the dependent variables linked to the 15-minute city, political participation, information, and use of the internet, as indicated in the literature. In line with the research question, we grouped the variables in groups related to the participation, digitalisation, political life, and accessibility. Therefore, the variables used can be grouped into the following groups (Table 1).

Table 1 shows some variables used according to the purpose of the research, in line with the empirical evidence. As spatial variables, the mode of travel (train, bicycle, car-sharing, bike-sharing) was considered to represent both proximity and accessibility. The dataset also provides the ease of reaching places of interest within 15 minute or with ease. For the transport section, we also considered the ownership and use of bicycles, motorbikes, as a counterbalance to car use, which is against the concept of the x-minute city, to place more emphasis on walkability and easy access between neighbourhoods [52, 53, 56–64]. Socioeconomic variables offer valuable insights on the working conditions and movements of the population, as well as the habits and features of the population. Regarding the "ATECO" (classification of economic activities) condition, we refer to the trade class defined in Italy as ATECO [55]. In Table 1, grouped variables are highlighted to simulate the role of public participation, in debates, associations and decision-making processes; indicators were taken on participation in public life, use of connections (internet, WIFI), information (newspapers, magazines, TV, radio, smartphones, etc.):

- Trust in institutions (Italian/European Parliament, government, municipalities, associations, scientists);
- Participation in political debates, associations, meetings (e.g. 'Comizi', 'Cortei');
- Political distrust and dissatisfaction in parties, associations, public bodies.

Considering the conflicts but also of the literature on e-democracy, these variables consider the information and debate habits of Italian citizens. The variables adopted can represent both the link between citizens' satisfaction in the 15 minute (measured by different indicators) and to assess any dissatisfaction and distrust in public life, which could give rise to nimby phenomena, or towards figures such as scientists, who promote

Table 1. Variables of the case study, elaboration of author

Sector	Name of variables	Type of variable
Socio-economic	Sex Marital status Working position Past works ATECO condition Income Citizenship Same common displacement Intra-municipal/intra-provincial/inter-regional trips Job satisfaction General satisfaction with one's life	Categorical/ Ordinary
Mobility	Use of train/metro/bus/carpooling Use car as driver/passenger Use of motorbikes/bikes	Categorical
Accessibility	Free time Perception and satisfaction of the environment Satisfaction on urban settlement Tram, bus, bike, train use Use of green vehicles such as bike-sharing and carsharing Confidence in walking	Categorical/ Ordinary
Trust in political life	Trust in political/scientific institutions	Categorical
Knowledge and know-how of citizens	Information and earning know-how	Categorical
Participation in political life	Participation in political debates, associations, Comizi, Cortei	Categorical

scientific measures in the practical field. The concept that "the citizen makes a journey lasting 20–35 min, so is willing to travel for 15 minute" can be expressed through the 15-minute accessibility, which has been measured in relation to bike ownership. The other variables do not allow us to measure the 15-minute city in terms of proximity and accessibility due to endogeneity problems, so they were treated as independent variables. Satisfaction in work and life was also used as a variable to represent the general course of the citizen's life.

The dataset contains the questions 'satisfaction with one's private life' and 'satisfaction with one's job'. The dependent variable chosen closest to the research question is 'satisfaction with one's job'. The variable bicycle ownership plays the role of an instrumental variable, which is linked to the possibility of commuting within 5 km, maximum 20 min. This variable implies that ownership implies use, so it is more likely to be used for short trips between neighbourhoods. Political participation measures how active the citizen is in decision-making processes.

Then, the dependent variables identified are:

- Overall job satisfaction;
- Accessibility to services;
- Bike ownership;
- Political participation.

Table 2. Descriptive statistics of dependent variables.

Variable	Observation	Mean	Std. Dev	Min	Max
Job Satisfaction	15,86	2.05	0.69	1	4
Politic participation	39,75	0.18	0.33	0	1
Accessibility	45,59	0.78	0.42	0	1
Bike ownership	45,59	0.59	0.49	0	1

The model chosen for the cross-sectional data is based on a regression analysis to identify the factors influencing the dependent variable, to understand the factors influencing the performance of participation citizens and thus the choice for the city of x minutes. For the current dataset, we chose more than one independent variable. For this reason, we adopt a multivariate regression analysis that helps to identify the relationship between the dependent variable and several independent variables simultaneously Table 2.

The model of multivariate regression [59, 60] follow the equation:

$$Y = X * B + \Xi \tag{1}$$

where Y be the n × p response matrix, the vector X is an n × (q + 1) matrix including the predictors. The matrix value B be an (q + 1) × p matrix of fixed parameters, Ξ be an n × p matrix such that Ξ∼N (0,Σ) (multivariate normally distributed with covariance matrix Σ. The examination of the correlations between the equations' residuals, needs the inclusion of the correlation option during the setting of the model, that is based on the $\chi 2$ statistic as Lagrange multiplier statistic, as provided by [61, 62]. In absence of pedestrian mobility variables, we considered bicycle ownership - which includes the use of bicycles as a means of transport, participation in bike-sharing programmes and the use of bicycles as an intermodal mode as an instrumental variable encouraging walking and general life satisfaction. Regarding the descriptive statistical analysis, 35% of the respondents were satisfied with their work. Of these, 71% gave positive feedback (highly satisfied), while the remaining 29% were moderately satisfied (Fig. 1).

Regarding travel habits, 32% make intra-provincial journeys, while only 26% travel within their city. These results have implications for the possibility of decreasing car use in favour of walking or cyclin (Fig. 2). On accessibility, the ease of reaching main services is rather low, only 16% easily reach the hospital, 19% the police office, and super-markets (19–20%).

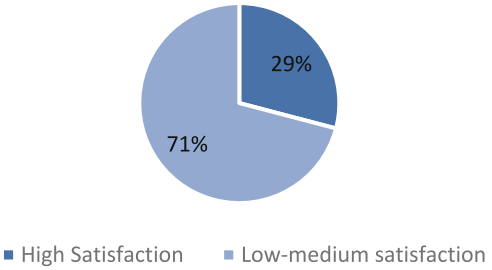


Fig. 1. Percentage of job satisfaction, elaboration of authors.

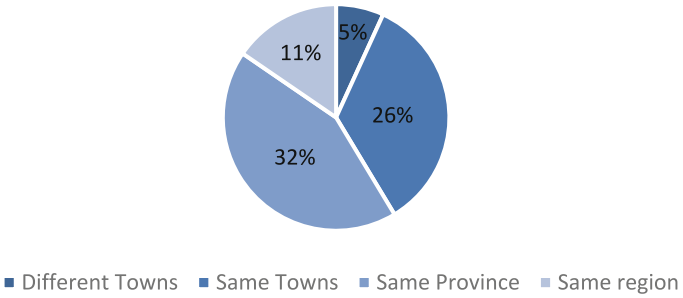


Fig. 2. Type of trips, elaboration of authors.

4 Results and Discussions

The analysis conducted highlights the relationships between accessibility, political participation, and citizen satisfaction.

The analysis of the dependent variables has been conducted for the socio-economic sector, the political sector, accessibility and proximity, mobility, and further variables (free time, use of other means of transport). The dependent variables such as ownership of a bicycle, the participatory political sphere, represent three moments for implementing the 15 minute city under three different aspects: the first is public participation, measured as technology and use of technology (both for information both in general and for politics), the bicycle is used to symbolize a tranquil existence that prevents uprisings by simulating a citizen's capacity to travel sustainably, across small distances, and for their own benefit.

The results are organized in Tables 3, 4, 5 and 6 into three groups: the first group collects the results for the bike use relating the socio-economic, mobility and accessibility sectors, the second for mobility and accessibility, and the third concerns the political sphere. The results generally show a positive correlation with trust in institutions. In detail, citizens' satisfaction in terms of work towards the Region and among scientists decreases, and participation in associations makes them dissatisfied. Regarding technologies, owning a television does not influence personal satisfaction or political participation and is of little importance to owning a bicycle. Personal satisfaction is

measured both as satisfaction with one's working life and in general, they are both self-reported (Likert scale) therefore we considered it valid to use the work environment as an indicator linked to accessibility and travel, rather than satisfaction with private life, which depends on much more subjective reasons, which go beyond the accessibility and proximity of services. In relation to the other variables, bike ownership and the ease of reaching green areas underlines that use decreases if there is a feeling of degraded landscape and environment of where one lives, just as accessibility is negatively influenced by neighbourhood conditions in very bad condition. The use of the car indicates an absence of bicycle use, while those who own a bicycle are more in favour of using two-wheeled means of transport but believe that it is dangerous to go around alone on the street. Those who own a bike seem to have a positive idea of trust in institutions and are satisfied with life in general. On the environmental aspect, bike ownership is not favoured by a polluted environment). These results lead us to believe that there are favourable conditions to encourage mobility within 15–20 min, as bike ownership is positively correlated with environmental, political, and socio-economic variables. Nonetheless, based on the findings about public engagement and personal satisfaction, individuals who are content are associated with higher incomes but have mistrust for government agencies. In conclusion, the use of digital tools (computers, Wi-Fi, information from radio and TV, etc.) has no impact on public engagement. Consequently, we may conclude that although possessing and using digital technologies alone does not always result in social and political participation or interest manipulation, they do so through the use of other digital typologies. The part on public participation is positive with the satisfaction of free and meaningful time, as well as participation in various social gatherings ('comizi', 'cortei', other associations). Citizens that participate in political debates have trust in the institutions and have shown themselves in favour of the use of bike sharing in the last year. Regarding accessibility and the environment, there is concern about air pollution, road safety and crime, and the ability to find parking. On accessibility, the use of the train is the only significant means of transport, while they do not easily reach destination places such as supermarkets.

In relation to the 15-minute city, the use of the bike positively influences indicators of proximity and accessibility, suggesting that owning a bike does not make citizens satisfied, but helps them reach city services such as municipal offices, supermarkets, pharmacies, is positive with the satisfaction of your free time, and also demonstrates an important aspect that emerged, or environmental sensitivity (Air pollutant variable).

Citizens that own bikes and travel by other sustainable means (carpooling) are also concerned about the environment, about air quality, noise and public safety. This result can be interpreted as an incentive to use the bicycle and both for the 15-minute city and by creating distances that can be covered by bicycle, citizens can reduce their sense of concern for the environment in terms of pollution. A further aspect to consider is safety, which indicates how safe citizens feel when walking. The safety variable responds to the variable "How safe do you feel walking down the street when it is dark and you are alone in the area where you live?" and being a Likert variable (1 = very safe, 6 = I never go out), it leads us to think that with the bicycle citizens feel safe walking at night because where they move there is a safe condition. The socio-economic variables are not significant except for age and gender. In relation to institutions, citizens who trust

Table 3. Results of variable use of bike.

Bike Use	Coefficient	Std. Err	t	P > |t|	95%	conf. interval
Age	–.024	.006	–3.75	0.000	–0.036	–.011
Sex	.026	.009	2.64	0.008	.006	.045
Instruction	–.001	.001	–2.77	0.006	–.001	–.000
Tram	.034	.004	7.78	0.000	.025	.043
Train	–.039	.005	–7.10	0.000	–.050	–.028
Landscape	–.050	.010	–4.93	0.000	–.071	–.030
Motorbike	–.015	.003	–4.00	0.000	–.022	–.007
Car Use	–.035	.003	–10.48	0.000	–.042	–.028
Life satisfaction	.014	.002	5.44	0.000	.009	.019
Hospital	–.039	.006	–6.28	0.000	–.051	–.027
Commercial office	–.030	.009	–3.33	0.001	–.048	–.012
Safety	–.011	.003	–3.11	0.002	–.019	–.004
Trust Institution	–.008	.002	–4.15	0.000	–.013	–.004
Parking facility	.046	.004	11.57	0.000	.038	.054
Connection to means of transport	.012	.003	3.53	0.000	.005	.018
Air pollutions	–.032	.005	–5.72	0.000	–.043	–.021

the government have access to associations but also a good connection with the territory, as emerges from the proximity and accessibility indicators.

These results show that public participation is not linked to the use of smartphones but to how active citizens are in communities and participation associations, therefore it suggests that citizens, rather than informing themselves online, prefer to dialogue and discuss, participating in the sector. Furthermore, it shows that sustainability measures can favour measures to reduce pollution, since we tried to analyse the car variable (such as driver and passenger) but it was never significant. Citizens who own a bicycle use alternative means of transport and may be in favour of green policies to reduce pollution.

The only sociological problems that arise with the emergence of syndromes are mistrust of scientists and local government. There are several possible causes for this result. First, since the dataset is for the year 2021 and we are during the COVID-19 pandemic, there was a lot of misunderstanding about the scientific role at the time. To help citizens and prevent them from feeling abandoned, we believe that measures for the 15-minute city must start with a bottom-up approach and institutional interventions. This is because the measures promoted at regional level do not seem sufficient to build citizens' trust. Finally, there is the question of how to integrate means of mobility.

Table 4. Results of job satisfaction.

Job satisfaction	Coefficient	Std. Err	t	P > |t|	95%	conf. interval
Age	.024	.010	2.37	0.018	.004	.044
Sex	.057	.015	3.64	0.000	.026	.088
Income	.077	.016	4.76	0.000	.045	.110
Train	.027	.008	3.30	0.001	.011	.044
Free time	.154	.006	23.04	0.000	.141	.167
Environment	.156	.008	19.20	0.000	.140	.172
Landscape	.042	.014	2.82	0.005	.012	.071
Safety	.025	.005	4.89	0.000	.015	.035
Car use	.013	.004	2.88	0.004	.004	.022
Life satisfaction	–.173	.003	–47.24	0.000	–.180	–.166
Trust institution	–.014	.002	–7.32	0.000	–.018	–.011
Noise	–.035	.008	–3.92	0.000	–.052	–.017
Commercial Office	.041	.013	3.04	0.002	.014	.069
Market	.044	.018	2.43	0.015	.008	.079

Table 5. Results of mobility and accessibility.

Accessibility	Coefficient	Std. Err	t	P > |t|	95%	conf. interval
Tram	–0.023	0.003	–6.43	0.000	–0.030	–0.016
Train	–0.023	0.004	–5.01	0.000	–0.032	–0.014
Police office	–0.079	0.009	–8.26	0.000	–0.098	–0.060
Commercial Office	–0.042	0.007	–5.62	0.000	–0.057	–0.027
Market	–0.069	0.009	–7.01	0.000	–0.088	–0.050
Environment	–0.018	0.004	–3.82	0.000	–0.027	–0.008
Landscape	–0.064	0.008	–7.45	0.000	–0.081	–0.047
Safety	–0.019	0.003	–6.31	0.000	–0.026	–0.013
Car Use	0.008	0.002	2.85	0.004	0.002	0.013
Scientist trust	0.005	0.001	3.56	0.000	0.002	0.008
Connections	0.058	0.002	20.80	0.000	0.053	0.064

(*continued*)

Table 5. (*continued*)

Accessibility	Coefficient	Std. Err	t	P > |t|	95%	conf. interval
Traffic	0.014	0.004	3.05	0.002	0.005	0.024
Air pollution	–0.023	0.004	–5.06	0.000	–0.032	–0.014
Criminality	–0.0139	0.004	–3.26	0.001	–0.021	–0.005

Table 6. Results of politic participation group

Political particitpation	Coefficient	Std. Err	t	P > |t|	95%	conf. interval
Age	0.043	0.005	8.18	0.000	0.032	0.053
Sex	–0.027	0.008	–3.37	0.001	–0.043	–0.011
Instruction	–0.000	0.000	–2.24	0.005	–0.001	–0.000
Free time	0.018	0.003	5.57	0.000	0.012	0.025
Association participation	0.293	0.020	14.09	0.000	0.253	0.334
Participation in “Comizi”	0.437	0.017	25.32	0.000	0.403	0.471
Participation in “Cortei”	0.263	0.022	11.85	0.000	0.220	0.307
Safety	0.025	0.005	4.89	0.000	0.015	0.035
Car Use	0.013	0.004	2.88	0.004	0.004	0.022
Life satisfaction	–0.173	0.003	–47.24	0.000	–0.180	–0.166
Trust institution	–0.014	0.002	–7.32	0.000	–0.018	–0.010
Bike sharing	0.097	0.023	4.22	0.000	0.052	0.142
Parking facility	–0.008	0.003	–2.73	0.006	–0.014	–0.002
Air pollution	–0.011	0.004	–2.64	0.008	–0.019	–0.002

The use of buses and couriers is not significant while other proximity variables prevail, except for the train. This leads to considering greater capillarity between neighbourhoods that cannot be reached by trains and buses as the stations are located further away. From the analysis carried out, a national trend emerges from which Italian citizens do not seem to show syndromes towards accessibility and proximity indicators, while they show difficulties towards the central government. Institutional strengthening of the idea of governance applied to urban processes is consequently suggested. In conclusion, the lack of technological results does not provide much insight into digital democratic participation. Nevertheless, it does highlight the necessity of prioritizing institutional consensus and public participation when considering technological participation.

5 Conclusions

The analysis provides several results. Services are undoubtedly a component of the city of x-minutes, but its implementation is influenced by other individual factors. People enjoy quick excursions yet find it challenging to get to the key services, and their mobility is impacted by safety and environmental comfort. Concerning participation, there is little evidence of digital connectivity and ICT, however, as already mentioned, this figure is only an indicator of use and information, it does not prove that participation can be improved or not with ICT.

Based on these results, this study highlights possible areas for scientific and practical study. Firstly, analysing the role of the car that is still present and strong, and noting that if intermodally is reduced, the use of the car is still fundamental to getting around, and it creates discomfort in people that green means cannot offer. Secondly, lifestyle leads to the assumption that in rallies or associative participation, extensive and widespread accessibility measures should be considered, while many services are still out of reach. Conflicts may arise from imposing cycling without improving neighbourhood conditions, such as safety, decay, noise, crime, and pollution. Measures on the 15-minute city should be carried out on intermodality and the location of workplaces, to offer a mode of travel that makes people satisfied with their work and life.

ICT use of e-democracy and e-participation, as expressed in the literature, does not emerge from the results. The implementation of urban initiatives is limited by public trust in science and government, which may result in discontent given the correlation between political involvement, life satisfaction, and work satisfaction. From the results, we can conclude that reaching consensus depends more on the surroundings. Based on the data, we can conclude that people are sensitive to political debates regardless of the medium, and that car use still predominates [63, 64].

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

References

1. Marquet, O., Mojica, L., Fernández-Núñez, M.B., Maciejewska, M.: Pathways to 15-Minute city adoption: can our understanding of climate policies' acceptability explain the backlash towards x-minute city programs? Cities **148**, 104878 (2024)
2. Ratti, C.: Don't let the culture wars sabotage 15-minute cities (2024). https://www.japantimes.co.jp/commentary/2024/01/05/world/15-minute-cities-study-conspiracy/. Accessed 08 May 2024
3. Michollek, N., Baig, R.: Fact check: Are 15-minute cities a plan to create lockdowns? (2023). https://www.dw.com/en/fact-check-are-15-minute-cities-creating-new-lockdowns-and-movement-restrictions/a-65226117. Accessed 08 May 2024
4. O'Sullivan, F.: Where the '15-Minute City' Falls Short (2021). https://www.bloomberg.com/news/articles/2021-03-02/the-downsides-of-a-15-minute-city?embedded-checkout=true. Accessed 08 May 2024
5. Chamberlain, L.: The surprising stickiness of the "15-minute city" (2022). https://www.weforum.org/agenda/2022/03/15-minute-city-stickiness/. Accessed 08 May 2024

6. Jackson, J.: What is the 15-minute cities conspiracy theory (2023).https://www.thebureauinvestigates.com/stories/2023-10-04/what-is-the-15-minute-cities-conspiracy-theory/. Accessed 08 May 2024
7. Evans, E.: How opponents of LTNs are adopting the climate-sceptic playbook. The Guardian (2023). https://www.theguardian.com/uk-news/2023/may/18/how-opponents-of-ltn-are-adopting-the-climate-sceptic-playbook. Accessed 08 May 2024
8. The Globe, Opinion: The '15-minute city' controversy is based on bunk. The fear behind it is worth considering, The Globe and Mail, (2023). https://www.theglobeandmail.com/opinion/article-the-15-minute-city-controversy-is-based-on-bunk-the-fear-behind-it-is/. Accessed 08 May 2024
9. Carlton, R.: 15-Minute-City Conspiracy Theories Insane Says 15-Minute-City Creator (2023). https://www.forbes.com/sites/carltonreid/2023/02/08/15-minute-city-conspiracy-theories-insane-says-15-minute-city-creator/. Accessed 08 May 2024
10. Vinod Kumar T.M : Geographic Information System for Smart Cities. 1st edn. Copal Publishing Group, New Delhi (2014)
11. Vinod Kumar, T.M.: E-governance for Smart Cities. 1st edn. Springer, Singapore (2015). https://doi.org/10.1007/978-981-287-287-6_1
12. Vinod Kumar, T.M: Smart Economy in Smart Cities. 1st edn. Springer, Singapore (2017). https://doi.org/10.1007/978-981-10-1610-3_1
13. Vinod Kumar, T.M.: Geographic Information System for Smart Cities. 2nd edn. Copal Publishing Group (2016)
14. Vinod Kumar, T.M. State of the Art of E-Democracy for Smart Cities. In: Vinod Kumar, T. (eds.) E-Democracy for Smart Cities. Advances in 21st Century Human Settlements. Springer, Singapore (2017). https://doi.org/10.1007/978-981-10-4035-1_1
15. Olokesusi, F., Aiyegbajeje, F.O.: E-Democracy for smart city lagos. In: Vinod Kumar, T. (ed.) E-Democracy for Smart Cities. Advances in 21st Century Human Settlements. In: Smart economy in smart cities. Springer, Singapore (2017). https://doi.org/10.1007/978-981-10-4035-1_2
16. Casarin, G., MacLeavy, J., Manley, D.: Rethinking urban utopianism: the fallacy of social mix in the 15-minute city. Studi urbani **60**(16), 3167–3186 (2023)
17. Grönlund, Å.: E-democracy: in search of tools and methods for effective participation. J. Multi-Criteria Decis. Anal. **12**(2–3), 93–100 (2023)
18. Akmentina, L.: E-participation and engagement in urban planning: experiences from the Baltic cities. Urban Res. Pract. **16**(4), 624–657 (2023)
19. Mueller, S., Vatter, A.: Switzerland (Swiss Confederation) governing with 26 cantons, 4 languages and frequent referendums. In: The Forum of Federations Handbook of Federal Countries 2020, pp. 341–352. Springer International Publishing (2020). https://doi.org/10.1007/978-3-030-42088-8_25
20. Granier, B., Kudo, H.: How are citizens involved in smart cities? Analysing citizen participation in Japanese"smart communities". Inf. Polity **21**(1), 61–76 (2016)
21. Moreno, C., Allam, Z., Chabaud, D., Gall, C., Pratlong, F.: Introducing the "15-minute city": sustainability, resilience and place identity in future post-pandemic cities. Smart cities **4**(1), 93–111 (2021)
22. Khavarian-Garmsir, A.R., Sharifi, A., Sadeghi, A.: The 15-minute city: urban planning and design efforts toward creating sustainable neighborhoods. Cities **132**, 104101 (2023)
23. Stratigea, A., Papadopoulou, C.A., Panagiotopoulou, M.: Tools and technologies for planning the development of smart cities. J. Urban Technol. **22**(2), 43–62 (2015)
24. Manville, M., Cummins, B.: Why do voters support public transportation? Publ. choices private behave. Transp. **42**, 303–332 (2015)
25. Pagliara, F., Di Ruocco, I.: How public participation could improve public decisions on rail investments? Reg. Sci. Policy Pract. **10**(4), 383–404 (2018)

26. Willberg, E., Fink, C., Toivonen, T.: The 15-minute city for all?–Measuring individual and temporal variations in walking accessibility. J. transp. Geogr. **106**, 103521 (2023)
27. Åström, J.: Mot en digital demokrati?: teknik, politik och institutionell förändring (Doctoral dissertation, Örebro universitetsbibliotek) (2004)
28. Abu-Shanab, E., Knight, M., Refai, H.: E-voting systems: a tool for e-democracy. Manag. Res. Pract. **2**(3), 264 (2010)
29. Saglie, J., Vabo, S.I.: Size and e-democracy: online participation in Norwegian local politics. Scand. Polit. Stud. **32**(4), 382–401 (2009)
30. Yu, Z., Wang, Z., Jie, W.: Effect of digital skills on citizens' digital participation: mediating effects of political interest, social issues concern and national identity. Kybernetes, (2024). https://doi.org/10.1108/K-08-2023-1567
31. El-Sherif, D.M., Khalil, E. E.: Policy instruments for facilitating smart city governance, Smart Cities Policies and Financing, pp. 305–317 (2022). https://doi.org/10.1016/B978-0-12-819130-9.00052-8
32. Guziana, B.: Only for Citizens? Local political engagement in Sweden and inclusiveness of terms. Sustainability **13**(14), 7839 (2021). https://doi.org/10.3390/su13147839
33. Anastasiadou, M., Santos, V., Montargil, F.: Which technology to which challenge in democratic governance? An approach using design science research. Transform. Gov. People Process Policy **15**(4), 512–531 (2021). https://doi.org/10.1108/TG-03-2020-0045
34. Mahrer, H., Krimmer, R.: Towards the enhancement of e-democracy: identifying the notion of the 'middleman paradox.' Inf. Syst. J. **15**(1), 27–42 (2005)
35. Tomor, Z., Meijer A., Michels A., Geertman S.: Smart governance for sustainable cities: findings from a systematic literature review. J. Urban Technol. **26**(4), 3–27 (2019).
36. Macintosh, A.: E-Democracy and E-Participation Research in Europe. In: Chen, H., et al. Digital Government. Integrated Series In Information Systems, vol. 17. Springer, Boston, MA (2008). https://doi.org/10.1007/978-0-387-71611-4_5
37. Bassoli, M.: Participatory budgeting in italy: an analysis of (almost democratic) participatory governance arrangements. Int. J. Urban Reg. Res. **36**(6), 1183−1203 (2012)
38. Boonstra, B., Boelens, L.: Self-organization in urban development: towards a new perspective on spatial planning. Urban Res. Pract. **4**(2), 99–122 (2011)
39. Conroy, M.M., Evans-Cowley, J.: E-participation in planning: an analysis of cities adopting on-line citizen participation tools, environment and planning. C Gov. Policy **24**(3), 371–384 (2006)
40. Cropf, R. A., Benton, M.: Towards a Working Model of e-Participation in Smart Cities: What the Research Suggests, In E-Participation in Smart Cities: Technologies and Models of Governance for Citizen Engagement, edited by, M. P. Rodríguez Bolívar, and L. Alcaide Muñoz, 99–121. Cham: Springer, (2019)
41. Royo, S., Yetano, A.: "Crowdsourcing" as a tool for e-participation: two experiences regarding CO_2 emissions at municipal level. Electron. Commer. Res. **15**, 323–348 (2015)
42. Molinari, F., Ferro, E.: Framing Web 2.0 in the process of public sector innovation: going down the participation ladder. Eur. J. ePract. **9**(1), 20–34 (2009)
43. Edelmann, N., Höchtl, J., Sachs, M.: Collaboration for open innovation processes in public administrations. Empowering Open Collaborative Governance Technol. Methods Online Citiz. Engagem. Public Policy Making, 21–37, (2012)
44. Arnstein, S.R.: A ladder of citizen participation. J. Am. Inst. planners **35**(4), 216–224 (1969)
45. C40 Cities Climate Leadership Group. How to build back better with a 15-minute city (2020).https://www.c40knowledgehub.org/s/article/How-to-build-back-better-with-a-15-minute-city. Accessed 08 May 2024
46. Miller, D.: Mayors engaging with the G20: Make COVID-19 recovery green and just to deliver a successful COP26 (2021). https://www.c40.org/news/mayors-engaging-with-the-g20-make-covid-19-recovery-green-and-just/. Accessed 08 May 2024

47. Spirakis, G., Spiraki, C., Nikolopoulos, K.: The impact of electronic government on democracy: e-democracy through e-participation. Electron. Gov. Int. J. **7**(1), 75–88 (2010)
48. Bartzokas-Tsiompras, A., Bakogiannis, E.: Quantifying and visualizing the 15-minute walkable city concept across Europe: a multicriteria approach. J. Maps **19**(1), 2141143 (2023)
49. Vale, D., Lopes, A.S.: Accessibility inequality across Europe: a comparison of 15-minute pedestrian accessibility in cities with 100,000 or more inhabitants. npj Urban Sustain. **3**(1), 55 (2023)
50. Gaglione, F., Gargiulo, C., Zucaro, F., Cottrill, C.: Urban accessibility in a 15-minute city: a measure in the city of Naples. Italy. Transp. Res. procedia **60**, 378–385 (2022)
51. Staricco, L.: 15-, 10-or 5-minute city? A focus on accessibility to services in Turin Italy. J. urban mobility **2**, 100030 (2022)
52. Murgante, B., Patimisco, L., Annunziata, A.: Developing a 15-minute city: A comparative study of four Italian Cities-Cagliari, Perugia, Pisa, and Trieste. Cities **146**, 104765 (2024)
53. Molinaro, D., Santarsiero, V., Saganeiti, L., Murgante, B. (2023). The 15-minute City Model: Assessment of the Socio-Economic and Environmental Impacts Associated with the Location of Essential Amenities. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2023 Workshops. ICCSA 2023. Lecture Notes in Computer Science, vol. 14107. Springer, Cham. https://doi.org/10.1007/978-3-031-37114-1_32
54. Patimisco, L., Annunziata, A., Murgante, B.: Spatial and Configurational Analysis for the Implementation of the 15-Minute City Model. The Case Study of Perugia, Italy. In: International Conference on Innovation in Urban and Regional Planning, pp. 681–692. Springer Nature Switzerland, Cham (2023). https://doi.org/10.1007/978-3-031-54118-6_60
55. Italian National Institute ISTAT Homepage. www.istat.it. Accessed 08 May 2024
56. Vale, D.S., Saraiva, M., Pereira, M.: Active accessibility: a review of operational measures of walking and cycling accessibility. J. Transp. Land Use **9**(1), 209–235 (2016)
57. Knap, E., Ulak, M.B., Geurs, K.T., Mulders, A., van der Drift, S.: A composite X-minute city cycling accessibility metric and its role in assessing spatial and socioeconomic inequalities–a case study in Utrecht, the Netherlands. J. Urban Mobility **3**, 100043 (2023)
58. Kneuer, M.: E-democracy: a new challenge for measuring democracy. Int. Political Sci. Rev. **37**(5), 666–678 (2016)
59. Allison, P.D.: Multiple Regression. Pine Forge Press, Thousand Oaks, CA (1999)
60. Berry, W.D.: Understanding Regression Assumptions. Sage Publications, Newbury Park, CA (1993)
61. Breusch, T.S., Pagan, A.R.: The lagrange multiplier test and its applications to model specification in econometrics. Rev. Econ.Stud. **47**, 239–253 (1980)
62. Oberfichtner, M., Tauchmann, H.: Stacked linear regression analysis to facilitate testing of hypotheses across OLS regressions. Stata J. **21**, 411–429 (2021)
63. Päivärinta, T., Sæbø, Ø.: Models of e-democracy. Commun. Assoc. Inf. Syst. **17**(1), 37 (2006)
64. Manville, M., Cummins, B.: Why do voters support public transportation? Public choices private behave. Transp. **42**(2), 303–332 (2015)

Downscaling Strategic EU Policy Directions in Mediterranean Cities: Participatory Assessment of Critical Issues and Barriers

Anastasia Stratigea[1(✉)], Yiota Theodora[2], and Chrysses Nicolaides[3]

[1] School of Rural, Surveying and Geoinformatics Engineering, Department of Geography and Regional Planning, National Technical University of Athens, Athens, Greece
stratige@central.ntua.gr

[2] School of Architectural Engineering, Department of Urban and Regional Planning, Spatial Planning and GIS Laboratory, National Technical University of Athens, Athens, Greece
ptheodora@arch.ntua.gr

[3] Strategy Consultant and Advisor for Cities, Board Member of the EU Mission for Climate-Neutral and Smart Cities, Limassol, Cyprus
c.nicolaides@cytanet.com.cy

Abstract. The future of the European Union (EU) is today drafted by the 2050 climate-neutral vision, as this is expressed by the European Green Deal (EGD), i.e. a strategy/investment package for climate/environmental action, economic growth/jobs, and social inclusion; and a policy direction, displaying a strong focus on people/communities and providing incentives for impact-minded partnerships across sectors/geographies. In support of the EGD's priorities, the Mission on "Climate-neutral and Smart Cities" is deemed to accomplish a deep and systemic transformation of European cities and bring on board concrete solutions to contemporary challenges. 100 EU cities are, at first, taking over as vivid laboratories for achieving climate-neutrality by 2030 and steering efforts of all European cities towards the 2050 vision. The focus of this paper is on stimulating a dialogue among the scientific, policy making and practitioners' communities on the above strategic policy directions; and exploring key issues as well as barriers applying to the downscaling of the EGD and particularly the Cities' Mission to the Mediterranean context. Towards this end, a blended participatory methodology is utilized, consisting of: a questionnaire addressed to the aforementioned communities that gathers distributed knowledge as to the key issues and barriers for successfully downscaling EU policy priorities to Mediterranean cities; and a Focus Group exercise, engaging stakeholders of diverse expertise for further delving into critical questionnaire results. Out of this exercise, prevailing barriers seem to be the lack of governance/collaboration and synergies' creation as well as the distinct structural and behavioural/cultural peculiarities of Mediterranean population.

Keywords: Mediterranean cities · European Green Deal · Mission for "Climate-neutral and smart cities" · Participatory assessment · Focus Group discussion

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 93–111, 2024.
https://doi.org/10.1007/978-3-031-65238-7_7

1 Introduction

Cities and regions around the globe are currently confronted with severe climate, environmental, energy, social, cultural, health, and economic crises that can radically affect their future pathways to sustainability. Such crises, as Yigitcanlar et al. [1] notice, are mainly due to the rapid population increase and the adoption of an excessively wasteful, beyond earth limits, consumption-driven way of living; while they are further deteriorating by the industrialization, the intense urbanization and mobility pattern, and the intensification of agricultural production for serving food sufficiency. Outcomes of such crises may result in life-threatening natural disasters, biodiversity loss, degradation of natural ecosystems, as well as regional disparities and socioeconomic inequalities, all placing an unbearable burden on national/regional economic, societal and natural ecosystems [2]. Attempts to reverse or mediate the impacts of those ominous outcomes are currently strongly based on global policy initiatives but also European/national ones, both grounded in nature-based and technology-enabled solutions as well as community awareness raising endeavours [3, 4], aiming to reduce the human footprint on earth.

Along the aforementioned *glocal* (global/local) efforts, Europe has placed itself in a protagonist position. In fact, Europe nowadays is perceived as a world leader in advocating environmental, social and governance (ESG) principles, properly adjusting its regulatory landscape in order for the European policies to be in alignment with these principles [5].

In this respect, a groundbreaking, strategic and long term policy initiative of the European Union (EU) is the 2019 *European Green Deal* [6], which constitutes an EU attempt to align with the United Nation's 2030 Agenda and achieve the SDGs; and formulates a new growth strategy and an investment package for climate and environmental action, economic growth/jobs and social inclusion. At the heart of this strategy lie more sustainable future pathways, enabling the EU transition into: a fair and prosperous society; a resource-efficient and competitive economy, marked by the decoupling of economic growth from resource use; and a continent seeking to achieve climate neutrality by 2050 [6]. Concurrently, the EGD: constitutes a huge and of long term *participatory planning* and *governance* challenge for the European continent, blending a strong focus on people and communities; provides incentives for impact-minded partnerships across sectors and geographies; steps up alignment with the UN Agenda 2030 and the SDGs; and shapes international cooperation, with the EU taking up global leadership via Green Deal diplomacy [7].

In order for climate neutrality to be reached, the EU has committed itself to reducing net GHG emissions by at least 55% by 2030, compared with 1990 levels; and has set up a clear and concrete *long term vision* towards climate neutrality by 2050. Strategic objectives of the EGD are downscaled to the member states' level by enforcing legislation updates and policy reforms as well as monitoring their implementation [7]. Furthermore, an ambitious Climate Change (CC) adaptation strategy is also incorporated in the EGD, while emphasis is placed on getting access to: spatial data and instruments in support of integrating CC into risk management practices; smart energy infrastructure; and digital transformation, all three perceived as critical means for reaching the EGD objectives [6].

Furthermore, the EU has put forward five *Missions* for effectively coping with the current overwhelming challenges and serving its policy priorities, the EGD included [7]. The goals set in these Missions are quite ambitious, seeking to bring concrete results by 2030. Towards this end, tight bridges are predicted among the research, policy and entrepreneurial communities, including European citizens. This, in turn, implies that the goals of each Mission will be cooperatively accomplished by a portfolio of actions, including research projects, policy and legislative initiatives.

Among the five EU Missions falls the one seeking to achieve *"Climate neutral and smart cities"* (henceforth Cities' Mission), justified by the critical role cities play in achieving climate neutrality by 2050, as also predicted by the EGD. In fact cities account for more than 70% of global CO_2 emissions [8], grasped thus as major contributors to climate mitigation efforts and accelerators of the green and digital transformation. As a starting point, Cities' Mission is predicted to deliver 100 climate-neutral and smart cities by 2030. These are perceived as the frontrunners of the Cities' Mission endeavour, as well as pilots and vivid laboratories of innovative actions and social experimentation to be spread to the rest European urban contexts that will follow till 2050.

The aforementioned EU strategic directions constitute a major challenge for *Mediterranean cities and communities*, i.e. a 'hot spot' region in many respects, namely environmental, CC, biodiversity, water scarcity, natural disasters, volume of solid waste generation [9]; and a vital and timely discussion in this particular region that exhibits a 20% faster rate of warming, compared to the rest of the world [10]. The latter is confirmed on the ground of estimations of the general warming and drying future trend that goes faster than the global one in the Mediterranean region, rendering thus Mediterranean a Climate Change (CC) hotspot [9, 11, 12]. Furthermore, CC impacts are expected to further exacerbate in the Mediterranean scenery due to other environmental challenges [13], emanating from changes in land use and land degradation, intense urbanization and overtourism, intensification of agricultural production, overfishing and pollution (air, land, rivers and ocean) [12]. These, in turn, imply a range of severe socioeconomic consequences and pressure on human and habitat health, energy demand and water stress, food safety and sufficiency, biodiversity health, drought incidents and fire risk, etc. [12, 14]. In fact, CC is the flagship and eventually the most warning challenge for the future of cities and territories in the Mediterranean Region, affecting both the natural and the human livelihoods; while CC pace and magnitude as well as its impacts are perceived as defining factors of stability risks in Mediterranean territories.

Speaking of the urban environments in the Mediterranean (henceforth MED), it should be noted that urbanization displays fast-escalating patterns [2, 15, 16], with almost 70% of the MED population residing in urban areas that are disproportionately affected by CC (i.e., heat waves, extreme weather events, air pollution). In fact the rate of urbanization in the eastern and southern MED is the highest in the world [17]. Rapid urbanization rate in the MED, in turn, entails that CC is expected to exacerbate challenges related to economic growth, environmental degradation, urban risks, protection/preservation of cultural heritage, and migration, to name but a few. In this respect, identifying peculiarities or bottlenecks that may impede downscaling of the aforementioned EU strategic directions to the MED Region and especially the MED cities becomes a major policy concern in order for the respective territories that are in front of extreme

CC and other risks [12] to move towards more sustainable, resilient and climate-neutral pathways. Such a transition can, among others, be hampered by the specific attributes of MED cities, namely their size – small and medium cities – that renders them rather weak and lagging behind in terms of technology-enabled solutions to urban sustainability, especially cities in the southern and eastern less developed MED rim [1]. In addition, MED cities are sharing some distinct attributes compared to other European ones in: *economic terms* (nodes of tourism, culture, sea trade, etc. that are largely defining the economic wealth of MED societies); *geopolitical terms* (coastal and port cities at the cross roads of MED Sea, constituting avenues of trade and cultural exchange through centuries); and *cultural terms*, reflecting the mutual influence of its surrounding eastern and western civilizations through historically-deployed important commercial routes, all highly affected by but also contributing to the exaggeration of current CC challenges.

Based on the above discussion, the *focus* of this work is on the identification of *critical issues and barriers* that stem from the specific MED cities' context; and need to be overcome for successfully implementing the EGD and especially the Cities' Mission objectives in cities of both MED shores. This goal is accomplished by means of a two-step participatory framework that delves into specific, MED region-based topics and is composed of: i) a Web-based questionnaire aiming to gather distributed knowledge as to the key issues and the fundamental barriers for downscaling the EU strategies to MED urban environments; and ii) a Focus Group (FG) discussion that engages an interdisciplinary group of experts (practitioners, academia and policymakers) and aims at further delving into the most critical issues/barriers identified in the previous step. Results obtained illuminate *gaps* that need to be bridged in order for the benefits of the strategic EU directions in this transition era to be reaped by MED urban territories. The structure of the paper has as follows: in Sect. 2 the methodological framework and the context of the two participatory stages for gathering qualitative data as to the research topics of this work are sketched; Sect. 3 presents and discuss the results obtained by the two consecutive participatory stages; while, finally, in Sect. 4 key conclusions are drawn.

2 Data and Methodology

Qualitative data, collected and used in this work, emanate from a *two-stage participatory approach.* More specifically, in *Stage I*, a web-based questionnaire is utilised for gathering distributed knowledge from a number of respondents [audience and Members of the Scientific Committee of the 4th Smart MED Conference, conducted in Athens, October, 2020; and Members of the International Geographical Union (IGU) Commission for the MED Basin], mostly originating from MED countries. In *Stage II*, a Focus Group discussion is planned and organized during the aforementioned Conference, structured around the most critical issues raising in Stage I; and engaging a number of mainly MED-related stakeholders (7 persons), owing diverse expertise with respect to the topics concerned in the MED cities.

This two-step participatory approach is embedded in the methodological framework of this work that is sketched in Fig. 1. More specifically:

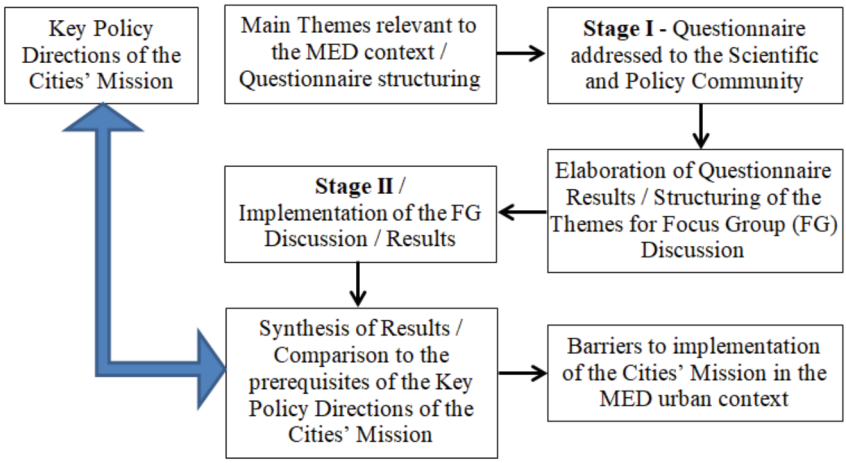


Fig. 1. Steps of the methodological approach, embedding participatory Stages I and II, Source: Own elaboration

- At first, a critical consideration of the European Green Deal and particularly the Cities' Mission is carried out, leading to the identification of core components for their successful implementation, as these are sketched in the introductory section.
- Then a number of main themes, related to the Mediterranean cities, are identified, justified by a literature review and authors' own experience. These have formed the ground for structuring and distributing a web-based questionnaire as a first step of the participatory approach, conducted in this work (Stage I in Fig. 1).
- Results obtained from this questionnaire are further elaborated and critical issues for the MED cities are identified and prioritized out of this participatory, distributed knowledge gathering, exercise. These have fed the structuring of a second participatory step – Stage II in Fig. 1 – organized by use of the Focus Group (FG) participatory method in a dedicated workshop, conducted during the Smart MED Conference (Athens, October 2020) [18].
- Next follows a synthesis of results of Stages I and II and their consideration against the core components for the successful implementation of objectives of the Cities' Mission. Such a consideration highlights the critical *barriers* that need to be overcome, thus guiding proper policy reaction for their alleviation.

2.1 Stage I - Structure and Audience of the Questionnaire

The questionnaire is structured in four main parts (Parts A to D), coupled with two complementary ones (Parts E and F) (Fig. 2). Within each main part, a number of key issues are listed for further prioritization, based on respondents' views.

More specifically, Part A is entitled "Resilience of Urban Environments". Resilience and smooth shocks' absorption seems to be critical in a globalized and rapidly changing world. This holds especially true for the MED, a place that is highly affected by CC impacts, but also the impacts of other unexpected incidences [migration surge, (geo)political tensions, natural disasters, economic recession, etc.], rendering it a "hotspot" in many respects [9].

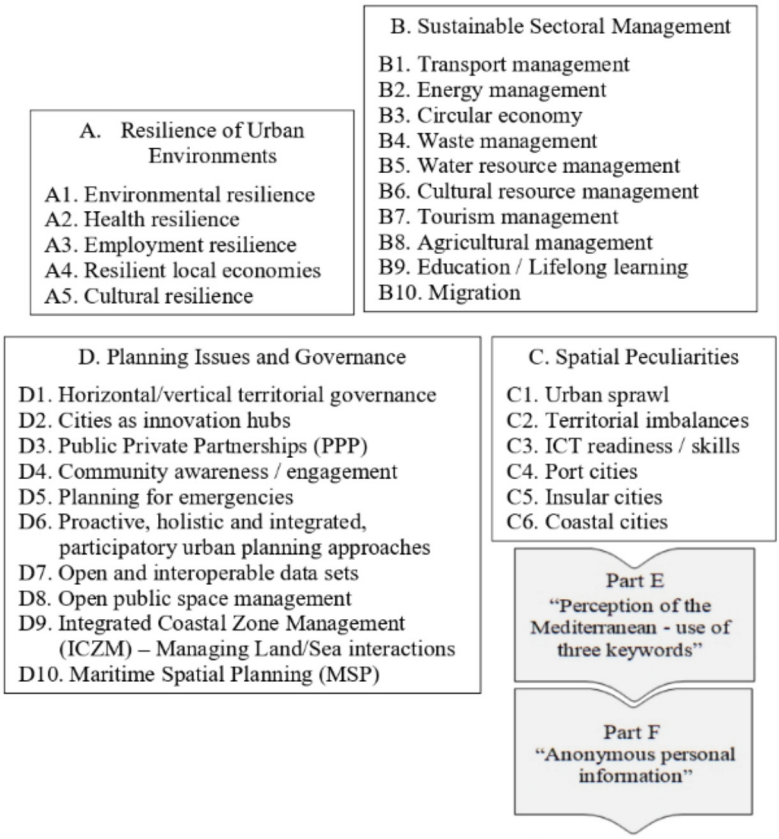


Fig. 2. Main and complementary parts of the questionnaire - Key issues explored in the main questionnaire parts A to D, Source: Own elaboration

Part B relates to the "Sustainable Sectoral Management". It attempts to shed light on a number of resource-intensive sectors, prevailing in the Mediterranean productive system; and raises key issues related to the sustainable management of these sectors in the urban context. Related challenges need to be cooperatively dealt with by the scientific, industry, civic and policy community.

Part C makes an effort to identify important "Spatial Peculiarities" of the MED Region that need to be properly addressed when seeking to fulfill sustainability objectives in urban environments and implement the aforementioned mainstream EU strategies. A number of key issues are identified that are closely related to the very peculiar attributes of the MED urban contexts. These can be perceived as both opportunities and obstacles in terms of implementing the EGD and particularly the Cities' Mission strategic policy directions.

Part D attempts to illustrate emerging "Planning Issues and Governance". It takes for granted that emerging challenges, demarcating the future of urban communities in general and those located in the MED region in particular, bring to the forefront: i) new

planning issues/problems, e.g. CC and sea level rise and their impacts, Blue Growth Economy and sustainable management of maritime resources, intense coastalization and Integrated Coastal Zone Management; and ii) approaches such as multi-level governance, bottom-up planning trails, Maritime Spatial Planning and Integrated Coastal Zone Management, to name but a few, for reaching the newly emerging policy targets. An indicative number of key issues that need to be highlighted and handled for achieving targets of the new urban agendas in MED cities as well as the barriers applying to their implementation are illuminated in this part for further commenting/prioritization by respondents.

Part E consists of a complementary questionnaire part, in which respondents are requested to express their perception of Mediterranean cities by using three keywords. These keywords are used for preparing a cloud word map, largely reflecting both positive and negative challenges currently faced or expected to affect future urban developmental trails in the MED in the medium to long term. This cloud word map can be used as a means for increasing awareness and communicating the key drivers of cities' change in this particular region of the world.

Finally, Part F contains certain (anonymous) personal information.

Table 1. Barriers explored as to the implementation of the strategic EU policy directions in the MED cities

a/a	Type of barrier
Bar-1	Limited funding
Bar-2	Lack of governance
Bar-3	Behavioural/cultural issues
Bar-4	Knowledge gaps
Bar-5	Lack of collaboration and synergies' creation
Bar-n	Other (please specify)

The *key barriers* to the implementation of the strategic EU policy directions, explored in this work, are listed in Table 1. In addition, each respondent could also add issues that he/she perceived as important, and are missing from the questionnaire and the barriers' list.

The questionnaire was circulated through the Web in the time span August 9 to September 10, 2020 (one month). It addressed *284 persons* in total, representing members of the academic community, young researchers, practitioners, and policymakers who were engaged in the Smart MED Conference [18]; and has led to a crop of *81 questionnaires* (28% of sample recipients).

With respect to the *region of origin*, the majority of respondents (68 persons or 84%) comes from MED EU countries. On the contrary, MED non-EU and non-Mediterranean respondents are underrepresented in the sample (7 persons or 9% and 6 persons or 7% respectively). Despite the low representation of these two groups, especially of the MED non-EU one, respective responses have been taken into consideration in this work. Such

a decision reflects the shared view of co-authors that sustainability objectives in the MED neighborhood call for a cooperative spirit and efforts of both the EU and non-EU states; and orchestrated endeavors are needed for dealing with shared challenges and shaping a common, worth-living destiny for their population. In addition, Mediterranean non-EU respondents can potentially raise diversified concerns or barriers towards the sustainable future of MED cities, grounded in the different decision environments they represent (cultural, technological, political, economic, etc.).

With regard to the *age group distribution*, 67.81% of respondents fall into the age group 36–55; while responses are also gathered from the age groups of 18–25 (4.5%), 26–35 (10.12%), 56–65 (14.17%) and 65 + (3.4%). From a *professional point of view*, more than half of respondents (53.65%) come from the academia. Young researchers – (post)graduate students – are also incorporated in the sample (13.16%). Furthermore, the sample includes practitioners (12.15%) and a small number of policy makers (3.4%). Finally, as far as *gender* is concerned, a rather balanced share between males and females is displayed in the respondents' sample.

It should be noticed here that the results obtained in Stage I are indicative, since the respondents' sample is rather small and unevenly spatially-balanced in terms of respondents' origin. However, as these originate from people working out a variety of Mediterranean themes, they are useful as a first attempt to highlight critical issues for further elaboration in the context of the FG endeavour (participatory Stage II).

Questionnaire respondents are invited to assess and prioritize the three most important *key issues* of each main theme (A-D in Fig. 2) and the three most important *barriers* (Table 1) inherent in the MED urban context in order for: effective management of these issues to be achieved; and current European mainstream strategies to be effectively integrated into respective MED urban ones. Towards this end, they are requested to rate them as follows: 1- important, 2 - very important, and 3 - highly important.

2.2 Stage II – Focus Group Discussion

Stage II of the participatory framework aims at delving into the most challenging key issues outlined in Stage I and related barriers that can impede implementation of the European strategic directions – EGD and especially the Cities' Mission – in MED cities. The selection of FG participants is guided by expertise, availability and willingness to engage in further highlighting the major issues of the MED urban environments with regard to the implementation of these directions. Taking into consideration that this FG workshop took place in the context of the 4thSmart MED Conference (Athens, October 2020 – [18]), the prevalence of Greek participants (Table 2) is justified.

A FG discussion took place on October 9, 2020, by chance of the 4th Smart MED Conference [18]. The duration of this discussion was approximately two hours and was structured as follows: at first, the key results of Stage I were presented to the FG participants; then discussion was structured around the main barriers to the implementation of the EU policy directions, appearing in MED cities.

Table 2. Origin institution and country of the FG members.

a/a	Origin Institution	Origin Country
FG Moderator	Rapporteur of the Cities' Mission Board	Belgium
Participant 1	Senior Researcher, Hellenic Center for Marine Research (HCMR)	Greece
Participant 2	Officer of Ministry of Energy and Environment	Greece
Participant 3	Senior Researcher, Hellenic Institute of Transport (HIT)/Center for Research and Technology (CERTH)	Greece
Participant 4	Prof., National Technical Univ. of Athens	Greece
Participant 5	Prof., Arab Academy for Science, Technology and Maritime	Egypt
Participant 6	Former Mayor, Member of the Mission Board	Belgium
Participant 7	Researcher, representative of Union for the Mediterranean (UfM)	Spain

3 Qualitative Results

3.1 Stage I – Gathering Distributed Knowledge Through the Questionnaire

In this section, key results obtained through the participatory process of Stage I are discussed. More specifically, with regard to the prioritization of the *key issues* explored, these can be summarized as follows (Fig. 3):

- Part A. "Environmental and health resilience" lay high in respondents' ratings, followed by "Employment resilience". These reflect concerns as to the environmental deterioration and severe CC repercussions, appearing in MED cities; coupled with the impacts of CC and the long austerity/economic recession period on employment, experienced by MED urban contexts.
- Part B. "Energy and transport management", coupled with "Circular Economy" and "Waste management" are key issues (sectors) in the MED city context. This is largely justified, among others, by the insufficiently implemented local spatial plans; the dominance of the private transportation behavioural pattern; the escalating urban sprawl and related informal buildings; and the pressure exerted by the large number of tourists in a short time span, taking into account the highly rated tourism destination profile of most MED cities, especially the coastal and insular ones.
- Part C. When considering the spatial peculiarities of the Mediterranean urban context, urban sprawl rates first and is coupled with coastalization, i.e. the high pressure on coastal cities/areas. This result is justified by the coastal cities' position as globally acknowledged tourist destinations. This, in turn, brings to the forefront a range of spatial challenges met mainly in coastal cities; while results in certain territorial imbalances/inequalities that need to be handled, both within a city context (coastal part and the rest of the city) as well as among different cities (developed coastal vs lagging behind inland urban environments). In addition, a hot issue for the Mediterranean refers to the way insular cities, fraught with a number of inefficiencies due

to "insularity", can become equal players and have an even chance of reaping the benefits of the Cities' Mission strategy.

- Part D. "Community awareness and engagement" rates quite high in the respondents' view. This is also a crucial issue in terms of implementing the EGD and especially the Cities' Mission, claiming, among others, wide coalitions among all actors in urban ecosystems. A certain deficit in civic engagement in the decision-making processes is noticed in the MED and a lack of relative culture. The same holds for "Territorial governance both horizontally and vertically", i.e. the interaction among diverse decision-making bodies and stakeholders either within a specific urban entity (urban spatial level) or among hierarchically different spatial levels. Missing is also a place-based approach as a key component for strengthening the effectiveness of policy formulation and successful implementation. The notion of "Cities as Innovation Hubs" lays also high in respondents' views, stressing the importance of the ICTs' adoption/use in a variety of fields and cities' functions for reaping the benefits of the Knowledge Society and strengthening cities' competitiveness, effectiveness, inclusiveness, and quality of service provision. Of importance is also the "Planning for emergencies" as well as the 'Open public space management', with the latter being grasped in terms of both emergencies' confrontation and improvements in quality of life in the saturated MED urban contexts.

With respect to the *barriers* that need to be overcome for successfully handling the key issues raised in Parts A to D, it seems that "Lack of governance" is the prevailing one, rating first in all four main Parts (Fig. 3). Highly important is also the issue of "Limited funding", reflecting the scarcity of financial resources for serving medium to long-term urban developmental perspectives. It seems that the economic recession and austerity of the last decade in MED countries have strongly affected entrepreneurship as well as private and public investments in a range of fields, while also leading to an increasing bankruptcy rate for small and medium-sized enterprises and a growing unemployment rate. "Lack of collaboration and synergies' creation", although a bit lower rated, compared to the previously mentioned barriers, seems to be a crucial deficit for creating economies of scale and sharing efforts for handling important, and of common interest, key issues in the MED region. Things are even more complicated when taking into consideration "Behavioural/cultural issues", highlighting the lack of participation culture in decision-making processes. This is mainly the outcome of the lack of citizens' trust in the political system, coupled with the reluctance of the latter to shift from traditional to more cooperative and transparent decision-making schemes.

3.2 Stage II – Results of the Focus Group Workshop

At the heart of the Focus Group discussion were placed the two most critical barriers to the implementation of the European strategic directions, emanating out of Stage I. These are the "Scarcity of financial resources" and the "Lack of governance". The latter is perceived at both the horizontal and the vertical level (i.e., decision makers and stakeholders at the city context and the different spatial contexts respectively).



Fig. 3. Respondents' views in the questionnaire research as to the prioritization of key issues and barriers, Source: Own elaboration

Following the views of the FG participants, the first – "Scarcity of financial resources" – was likened to the *"elephant in the room"*, implying the huge investments and the radically diversified business models needed towards the transition of MED cities to climate neutrality. The second – "Lack of governance" – was likened to a *"giraffe"* which, however, is as big as the "elephant", though less visible and evident, while also less seriously taken by the majority of Mediterranean cities. According to the FG views, this is justified by the fact that the transition to climate neutrality implies a city's systemic change that needs to be approached in an integrated, far from silo-thinking, way; and, most importantly, an inclusive one, embedding all actors of the urban ecosystem in a sincere, fair, transparent, creative and consensus-seeking way. In fact, the European Commission has emphasized the importance of citizens' engagement in planning and implementing the quite ambitious Cities' Mission initiative, considering this issue as the *flagship* of the Mission's endeavour.

However, as FG participants claimed, participatory decision-making processes are not really embedded in the culture of the majority of MED cities nor citizens are *"… accustomed, educated and aware of their role and power"* in such a context. As a result, speaking of governance at the horizontal level – i.e. the city context itself – tight bonds between the local decision-making bodies and the rest of urban actors are loose or even missing; while citizens in Mediterranean cities do not really trust local administration and are not confident that their opinions are truly heard. Furthermore, according to the FG participants, *"… citizens are not really aware of the ambitions and goals of the EU with respect to the Cities' Mission"*, meaning the absence of an effective and well-established communication plan for widely spreading current urban challenges and risks as well as the ambitious Cities' Mission objectives, ensuring thus their understanding and ownership by all cities' stakeholders and citizens. Of relevance to such a communication plan, according to FG participants, are *"impacting images"* that can support awareness raising; and can affect willingness to engage and commit to the Cities' Mission objectives. As noticed in the FG discussion, *"… citizens need to feel that they can really play a role"*. It was also stressed the need for putting forward a bundle of incentives that can improve citizens' engagement and commitment in accomplishing Cities' Mission objectives. However, FG participants considered also as necessary the investment in more time-consuming and of longer term processes that are capable of: educating people; raising their awareness as to the current cities' challenges and risks as well as the citizens' critical role in reversing ominous trends; establishing trust and loyalty among various groups; and consolidating a *"spirit of belonging and a mind of change"*. *"What I do has an impact, it counts and it is heard"* should be the conviction for every city actor for achieving the Cities' Mission goals.

With respect to governance at the *horizontal level*, FG participants also supported the *"No one fits all"* principle or, stated differently, they claimed that *"… every city has its own DNA"*; recognizing also the *"distinct features of MED cities compared to the ones of the northern Europe"*. In addition, they noticed that despite the fact that MED cities have very much in common, e.g. civilization, urban sprawl, crowded cities, CC risks, etc., their study in the context of the Cities' Mission needs to adopt a *place-based approach*, having at its heart each single community's value systems and culture,

behavioural patterns and spatial/developmental peculiarities. As examples, FG participants stressed the prevalence of private transportation in the mobility pattern of MED citizens as well as the production of informal housing stock, both leading to deterioration of the urban landscape, land degradation and air pollution due to rising traffic. These are further worsening due to the tourism overload during the summer season. Community awareness, political will, and the articulation and implementation of collaboratively-designed policy measures are critical aspects for reversing these patterns and improving the quality of life in MED communities. Furthermore, although the role of citizens is placed at the heart of the Cities' Mission discourse, FG participants consider the role of decision-makers in the MED also a problematic one. In fact, they claimed that not only citizens but also politicians need to change the way they act and make decisions, shifting from traditional government to ICT-enabled, city- and citizen-specific as well as data-driven governance schemes. In doing so, FG participants stressed the need for: steady monitoring and progress assessment; use of crowdsourcing in support of data collection and updating; deployment of participatory platforms for facilitating community engagement and interaction; and adoption of ICT-enabled spatial data management, as relevant for ending up with more informed decisions. Finally, FG participants stressed the importance of cities' extroversion and networking for gathering evidence-based results and good practices from frontrunner cities in the Mission's endeavour.

As far as the *vertical level* is considered, the absence of bonds between decision-making bodies at the various spatial levels and their interaction for ensuring coordination of related policies – from the national to the regional/local level – is stressed. In fact, FG participants claimed that a certain fragmentation and a lack of steady and institutionally-defined interaction channels exist among decision-making bodies at various governmental layers. Innovative governance schemes are needed in this respect that can ensure the effective feeding of national policies by regional and local peculiarities; and, vice versa, the effective and consistent downscaling of national strategic policies to the regional/local level. Specific coordination schemes and related resources in order for the Mission's objectives to be spread to as many cities as possible can be used in this respect. A good example of such a scheme is established in Greece as a national initiative, networking a number of Greek cities and providing a leading role to cities that are perceived as nationwide champions with regard to the Cities' Mission goals, falling among the 100 frontrunners of the Mission.

3.3 Summarizing Results of Stage I and II

Implementing the strategic objectives of the EGD and particularly the Cities' Mission in coping with CC impacts and urban sustainability is a tremendous challenge for European cities in general and the MED ones in particular. It presupposes a clear focus on territorial governance, i.e. place-based and multilevel interaction that properly adapts to the various MED urban contexts. In addition, an essential prerequisite for successful implementation is community engagement in order for a broad ownership of the pathway to climate neutrality and sustainability to be achieved and dedicated efforts from all actors in each city's local ecosystem to be properly orchestrated. A long-term view seems to be also indispensable that expands beyond the narrow time constraints of elected local administrations; and suggests political consensus and consistency in planning and

implementing dedicated, long term policy paths. In more detail, the core components for the implementation of the Cities' Mission [19] are shown in Table 3; and are juxtaposed with the barriers or weaknesses inherent in MED urban environments that can hamper climate neutrality and sustainability achievements. Those barriers emanate from the questionnaire responses and the Focus Group discussion, while also being noticeable in current literature [9, 12, 20–22].

In Fig. 4, a cloud word map is produced for the MED urban territories, illuminating the strong points but also the vulnerabilities of these territorial entities, as these are grasped by the questionnaire research respondents and experts engaged in the Focus Group discussion.

Table 3. Barriers to implementing strategic directions of the Cities' Mission in the MED urban context, Source: Own elaboration

Core components for implementing the Cities' Mission	Barriers
Cities' administrative, technical and financing capacity	– Lack of administrative, technical and financing capacity/Inadequate competencies of local administrations to plan and implement the ambitious transition to climate neutrality – Lack of collaborative culture and tight bonds with the academia, civic society and entrepreneurial community for gathering distributed knowledge and co-designing local policies – Deficit in new business models engaging the public and private sector – Local administrations are still anchored in traditional financing schemes
Long term view	– Lack of a long-term, data-enabled and consensus-based vision and related plans – Focus on everyday community problems than on long term visionary goals – Short term viewpoint, closely linked to Mayors' administrative lifetime and driven by re-election motives
City governance models	– Lack of a governance culture – Focus rather on government and management of everyday problems than governance – Silo-based administrative schemes and organization culture – Lack of a more integrated and strategic planning perception – Lack of wider collaborations and creation of synergies both among cities as well as within each single city

(*continued*)

Table 3. (*continued*)

Core components for implementing the Cities' Mission	Barriers
'By and for the citizens' way of thinking/working – 'Citizens as agents of change'	– Lack of participation culture in decision-making processes – Participation more as an institutional "must" than as a real social/political innovation, producing added value for all – Limited use of ICT means for citizens/stakeholders' engagement and openness/transparency of decision-making processes – Lack of citizens' awareness-raising endeavours as prerequisites for addressing climate emergency and urban sustainability priorities
'Cities as innovation hubs' – Embedding powerful technologies in governance, trans-port, energy, waste management, etc	– Low level of transformation of governmental structures and processes towards a smart governance model – Use for ICTs in a fragmented way, focusing on distinct smart city projects – Lack of ICT-enabled innovation, data infrastructure and data-driven decision-making processes
'No one left behind' principle	Drawbacks of MED cities impeding realization of this principle: – Size of Mediterranean cities – i.e. small and medium-sized cities –disadvantage in terms of private funding attractiveness – Insular cities – Insularity repercussions e.g. constrained accessibility, technological immaturity – Coastal cities – huge efforts needed to overcome the high vulnerability to CC impacts, high pressure due to rapid coastalization and tourism pressure, lack of integrated approach of land/sea and their interaction
Multi-level & co-creative process	– Lack of governance culture at the horizontal/vertical level – Lack of synergies' creation
More strategic and integrated urban planning models	– Local plans mostly lack a strategic, integrated, participatory and long-term flavour



Fig. 4. Cloud word map based on data collected through the questionnaire and the FG discussion, Source: Own elaboration

4 Discussion and Conclusions

Cities nowadays are confronted with unprecedented challenges, associated with the rapidly changing climate, economic, social, cultural, technological and geopolitical scenery and related risks emerging out of them. On top of these challenges lies CC, constituting the flagship of European policies in the new millennium in seeking to achieve climate neutrality by 2050. In fulfilling this quite ambitious and tricky goal, cities are placed at the forefront as the main contributors to CC and a source of innovative solutions towards CC mitigation/adaptation [23]. Such a position is, among others, justified by the intensifying urbanization trends in the European continent. Particularly in the MED cities, intense urbanization, especially in coastal areas [24, 25]), has led to the increase of human pressure in the neighborhood of major cities and along the seacoast [9, 26], taking the form of population concentration, major expansion of construction activity and infrastructures, urban sprawl due to secondary housing and tourism facilities [15, 16], to name but a few.

As a means to cope with the severe impacts of CC on city contexts, the Cities' Mission of the EU [19] attempts to promote a new paradigm that is mostly grounded in innovation as well as empowerment and engagement of all actors of a city's ecosystem – citizens, businesses and other stakeholders – in shaping the way forward. Or stated differently, the challenge is to plan and implement dedicated structural changes in alignment with the visions and expectations of people, thus promoting a step-wise and consensus-building approach as to the way the transition to climate-neutral and smarter cities, ensuring quality of life of their population, will be attained. In such an effort, it is evident that each single city constitutes a distinct example, displaying its own attributes and culture; different levels of embedded smartness; diversifying natural and cultural attributes; discrete geographical and morphological peculiarities; and a diverse starting point for climate neutrality, all defining the *gap* that needs to be filled towards the desired

end state. Integrating data and distributed knowledge from a variety of stakeholders as well as members of the scientific community seem to be an effective blend for providing advice with regard to the obstacles that need to be overcome in order to achieve alignment and effective implementation of the Cities' Mission objectives to both urban and national/ regional policy makers.

In such a context, support to political leaders is crucial in order for weaknesses to be identified and ways to work them out to be established so that a fruitful, creative and inclusive environment for such an ambitious goal – climate neutrality – to be activated. Along these lines, the present work attempted to highlight barriers or obstacles in MED cities that can hamper them to embark on the Cities' Mission initiative. This perspective seems to be crucial for their future state, taking into consideration the intense CC impacts in the MED compared to other parts of the world. Research conducted in this work, based on gathering/interpreting distributed knowledge from a variety of stakeholders, unveils the important key issues that are potentially shaping the future of MED cities as well as the most prevailing barriers to meeting the Cities' Mission objectives. Several MED cities are now in the float of the Cities' Mission; and whether and how they will manage to overcome these obstacles and create a climate-neutral thus more human and qualitative future for their population, within the Cities' Mission context, remains to be proven. Repetition of such a participatory methodology in 2030 (target year for the pilot cities to achieve the Mission's goals) could unveil barriers that were relieved and those still in place, hindering potential of cities' endeavors to fully attain Cities' Mission goals.

Acknowledgments. We would like to cordially thank all those who engaged and expressed their views in both the web-based questionnaire research and the Focus Group workshop.

References

1. Yigitcanlar, T., Xia, B., Tucunduva Philippi Cortese, T., Sabatini-Marques, J. (eds.): City 4.0: digital transformation of urban settlements. Sustainability **16**(671), 1–3 (2024). https://doi.org/10.3390/su16020671
2. Stratigea, A., Kyriakides, E., Nicolaides, Ch. (eds.): Smart Cities in the Mediterranean - Coping with Sustainability Objectives in Small and Medium-Sized Cities and Island Communities. Springer Cham (2017a). https://doi.org/10.1007/978-3-319-54558-5. ISBN 987-3-319-54557-8
3. UNEP– United Nations Environmental Program: Raising Awareness of Climate Change - A Handbook for Government Focal Points. United Nations Office at Nairobi/Publishing Services Section/Nairobi, Kenya (2006)
4. Adhikari, B., Taylor, K.: Vulnerability and adaptation to climate change: a review of local actions and national policy response. Climate Dev. **4**(1), 54–65 (2012). https://doi.org/10.1080/17565529.2012.664958
5. Theodora, Y., Stratigea, A.: Climate change and strategic adaptation planning in Mediterranean insular territories: gathering methodological insights from Greek experiences. In: Gervasi, O., et al. (eds.) ICCSA 2021. LNCS, vol. 12958, pp. 100–115. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-87016-4_8.2021
6. COM(2019) 640 final: The European Green Deal. Communication from the Commission to the European Parliament, the European Council, the European Economic and Social Committee and the Committee of the Regions, European Commission, Brussels (2019)

7. Panagiotopoulou, M., Agalioti, M., Stratigea, A.: EU Mission on 'Climate-Neutral and Smart Cities' – Assessing readiness to join of 12 Greek cities. In: Gervasi, O., et al. (eds.) ICCSA 2023. LNCS, vol. 14105, pp. 657–675. Springer Cham (2023). https://doi.org/10.1007/978-3-031-37108-0
8. Dasgupta, S., Lall, S., Wheeler, D.: Cutting global carbon emissions: Where do cities stand? (2022). https://blogs.worldbank.org/sustainablecities/cutting-global-carbon-emissions-where-do-cities-stand. Accessed 05 Jan 2024
9. Stratigea, A., Leka, A., Nicolaides, Ch.: Small and medium-sized cities and insular communities in the Mediterranean: coping with sustainability challenges in the smart city context. In: Stratigea, A., Kyriakides, E., Nicolaides, Ch. (eds.) Smart Cities in the Mediterranean - Coping with Sustainability Objectives in Small and Medium-Sized Cities and Island Communities, pp. 3–29. Springer Cham (2017b). https://doi.org/10.1007/978-3-319-54558-5_1. ISBN 987-3-319-54557-8
10. WWF: The climate change effect in the Mediterranean - Six stories from an Overheating Sea: WWF Mediterranean Marine Initiative, Rome, Italy (2021). https://www.wwf.fr/sites/default/files/doc-2021-06/20210607_Rapport_The-Climate-Change-Effect-In-The-Mediterranean-Six-stories-from-an-overheating-sea_WWF-min.pdf. Accessed 02 Jan 2024
11. EEA - European Environment Agency: The European environment - State and outlook 2015. Publications Office of the European Union, Luxembourg (2015)
12. Cramer, W., Guiot, J., Marini, K. (eds.): Climate and environmental change in the Mediterranean Basin – Current situation and risks for the future. First Mediterranean Assessment Report. MedECC, Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France (2020). https://doi.org/10.5281/zenodo.7224821. ISBN 978-2-9577416-0-1
13. García-Nieto, A.P., Geijzendorffer, R.I., Baró, F., Roche, K.P., Bondeau, A., Cramer, W.: Impacts of urbanization around Mediterranean cities: changes in ecosystem service supply. Ecol. Ind. **91**, 589–606 (2018). https://doi.org/10.1016/j.ecolind.2018.03.082
14. El-Askary, H., Li, W.: Mediterranean Basin case study. United Nations Office for Disaster Risk Reduction (2021). https://www.preventionweb.net/files/78472_cs13.heshamelaskarycasestudydrought.pdf. Accessed 14 Jan 2024
15. Lagarias, A., Stratigea, A.: Coastalization patterns in the Mediterranean: a spatiotemporal analysis of coastal urban sprawl in tourism destination areas. GeoJournal **88**, 2529–2552 (2022). https://doi.org/10.1007/s10708-022-10756-8
16. Lagarias, A., Stratigea, A., Theodora, Y.: Overtourism as an emerging threat for sustainable island communities – exploring indicative examples from the South Aegean Region, Greece. In: Gervasi, O., et al. (eds.): ICCSA 2023, Part VII. LNCS, vol. 14110, pp. 404–421. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-37123-3_29
17. GRID Arendal: Urban population in the Mediterranean countries (n.d.). https://www.grida.no/resources/5932. Accessed 22 Dec 2024
18. 4th SnartBlueCity Euro-Mediterranean Conference - Exhibition: https://www.smartbluecity.com/. Accessed 26 Apr 2024
19. Dinges, M., Borsboom, J., Gualdi, M., Haindlmaier, J., Heinonen, S.: Mission area: climate-neutral and smart cities. European Commission (2021)
20. Woertz, E. (ed.): "Wise Cities" in the Mediterranean? Challenges of urban sustainability. CIDOB Editions, Barcelona (2018). https://www.cidob.org/en/publications/publication_series/monographs/monographs/wise_cities_in_the_mediterranean_challenges_of_urban_sustainability. Accessed 29 Dec 2023
21. MedECC Network (2019). https://ufmsecretariat.org/wp-content/uploads/2019/10/MedECC-Booklet_EN_WEB.pdf. Accessed 02 Jan 2024

22. Marava, N., Alexopoulos, A., Stratigea, A.: Tracking paths to smart governance: the case of Korydallos Municipality—Greece. In: Stratigea, A., Kavroudakis, D. (eds.) Mediterranean Cities and Island Communities. PI, pp. 81–112. Springer, Cham (2019). https://doi.org/10.1007/978-3-319-99444-4_4
23. Stratigea, A., Leka, A., Panagiotopoulou, M.: In search of indicators for assessing smart and sustainable cities and communities' performance. Int. J. e-Plann. Res. **6**(1), 43–73 (2017). https://doi.org/10.4018/IJEPR.2017010103
24. Imbrenda, V., Coluzzi, R., Lanfredi, M., Loperte, A., Satriani, A., Simoniello, T.: Analysis of landscape evolution in a vulnerable coastal area under natural and human pressure. Geomat. Nat. Hazards Risk **9**, 1249–1279 (2018). https://doi.org/10.1080/19475705.2018.1508076
25. Sutriadi, R.: Smart sustainable coastal areas. BIO Web Conf. **89**, 04004 (2024). https://doi.org/10.1051/bioconf/20248904004
26. Smiraglia, D., Cavalli, A., Giuliani, C., Assennato, F.: The increasing coastal urbanization in the Mediterranean environment: the state of the art in Italy. Land **12**(5), 1017 (2023). https://doi.org/10.3390/land12051017

Communal Resilience Framework

Ondrej Mital'(✉), Silvia Ručinská, and Miroslav Fečko

Department of Public Policy and Theory of Public Administration, Faculty of Public Administration, Pavol Jozef Šafárik University in Košice, 04011 Košice, Slovak Republic
{ondrej.mital,silvia.rucinska,miroslav.fecko}@upjs.sk

Abstract. The study investigates communal resilience, the key evolving phenomenon of the last decade. Resilience helps cities and municipalities handle the growing rate of natural and man-made crises, risks, disasters, and emergencies. The study uses a literature review and multiple case study method to examine measures and activities implemented by selected regional cities that strengthen communal resilience. Regarding the conditions of the Slovak Republic and the increasing importance of communal resilience, altogether 8 cases between 2022 and 2023 were analyzed, focusing on the partial components of communal resilience. Based on the literature review and presented case studies, six complementary components of the communal resilience framework have been identified, strategic approach, networking, stakeholder involvement, resource management, output quality, and environment. The main benefit of the developed communal resilience framework is its wide applicability for any type of communal unit. Simultaneously study contributes to the growing discussion on the standardization of communal resilience framework.

Keywords: Resilience · resilient cities · resilience framework · Slovak Republic

1 Introduction

Modern society is perceived as a complex system of mutual relationships between entities interacting across various spheres of life. The social progress and growth of society result in a high level of interdependency. Governments worldwide increasingly understand that different systematic threats and challenges, such as climate change, cybersecurity, migration, energy transition, or poverty, can interfere expected and required development of modern society.

Looking at the past decade, governments' preparedness for contradictory impacts of expected and non-predictable crises has created a base for the effective achievement of public policy goals and perceived quality of life. In this regard, scholars and practitioners have started investigating whether governments, regions, cities, and communities, are resilient enough to overcome the growing frequency of disturbances. Resilience has evolved as a multidimensional concept dealing with how a complex system operates under stress, mainly underlining the ability to absorb, recover, and prepare for future shocks [24, 48]. Communal resilience must be seen as the resilience of local self-government units, mainly cities and municipalities. Authors argue that the communal

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 112–130, 2024.
https://doi.org/10.1007/978-3-031-65238-7_8

resilience framework helps local self-government units resolve crises or emergencies caused by endogenous and exogenous factors.

The study has the ambition to realize preliminary research and investigate the communal resilience framework in the Slovak Republic. In this sense, the study examines measures and activities implemented by selected regional cities that strengthen communal resilience. Ahead of this analysis, the study examines, in a theoretical way, the multidimensionality of resilience, mainly focusing on communal resilience and its components. More precisely, the study examines, mainly with the use of the case study method, measures, and activities implemented by eight regional cities that strengthen the communal resilience framework, focusing on the partial components of communal resilience. Focusing on the conditions of the Slovak Republic and the increasing importance of communal resilience, altogether 8 cases between 2022 and 2023 were analysed. We presume that the communal resilience framework is a generic conceptual system composed of partial components, that help cities and municipalities to adapt and to recover from expected and unpredictable crises.

2 Resilience: Contemporary State of Knowledge

Public administration as a complex system should respond to trends of the last decades, such as globalization, interdependency, increased human population and mobility, and intensification and sophistication of modern information communication technologies. Resilience represents the concept of the capacity to proactively and reactively cope with shocks, surprises, adversity, and hard times [45]. Resilience is an important topic, if we consider the increased rate of challenges that governments have to face and deal with [72]. The growth of governmental reasoning of resilience is a logical response to a precarious and uncertain world [53].

Contemporary society is thanks to its dynamics challenging the abilities of different entities to conform with this changing social reality. Besides, the concept of resilience is a dynamic process, meaning that it is not static or trait-like [38, 59]. Resilience is a process that is influenced by numerous factors that can change over time [77].

2.1 Resilience as a Popular and Trending Multidimensional Concept

Resilience studies have increased over the past 10 years. However, some aspects of contemporary meanings of resilience were analyzed at the turn of the millennium. The term resilience comes from the Latin word “resiliens” which means “to bounce back” or “to rebound”. The contemporary meaning of the term resilience was introduced by Wildavsky’s publication Searching for Safety in 1988 [21, 82].

Resilience is mostly defined as the capacity of a system or entity to continue to function in situations when crises or shocks have occurred. The primary content or resilience was mainly identified with the ability to respond to crisis [9, 67]. Over time resilience’s meaning was widened to include various societal difficulties and disorders, such as poverty, homelessness, traumatic events, natural disasters, violence, war, and physical illness [32]. Resilience is much richer than trying to resist change and control it to maintain stability because resilience also deals with complex adaptive system

dynamics, true uncertainty, and the ability to learn to live with change and make use of it [28].

Contemporary society faces many sophisticated challenges, such as natural disasters and environmental issues (fires, floods, storms, or droughts), man-made situations (terrorist attacks or cyber-attacks), economic instability (financial or debt crisis, inflation, and unemployment), pandemics (COVID-19), social changes (migration, changing demographics, cultural challenges). In this regard, resilience has become a complex phenomenon with different multidimensional aspects. Theoreticians and practitioners from different spheres of life are continuously examining and improving resilience in sociology, economy, ecology, public administration, psychology, and other disciplines. Research is mostly focused on preconditions and the impact of resilient frameworks at the individual, organizational, local, regional, or national levels.

Multidimensionality of resilience has been proven by different studies from various scientific disciplines, such as medicine, health, and psychology [20, 32, 77], environment and ecology [2, 3, 78], management [6, 17, 18, 57], society and governance [28, 34, 44, 69], as well as engineering, industry, and technology [54, 81]. Cooperation and cross-field collaboration are very rare, but it could help to utilize positive impact on research and practice implications in different fields of our society [29].

Environmental and ecological aspects of resilience are mostly focused on predictable and nonpredictable natural disasters, as well as the ability of entities to be prepared and recover from these situations. Managing resilience focuses on system-level characteristics and processes, and the endurance of system properties in the face of social or ecological surprise [2]. Resilience means building the ability of a community to bounce back after hazardous events, rather than simply reacting to impacts, while the ability to rebound more quickly can reduce negative human health, environmental, and economic impacts [46, 55]. In this regard, environmental and ecological aspects of resilience can also be discussed in its connection to other spheres of life.

In medicine and psychology, resilience represents a phenomenon that secures good outcomes despite risks, sustained competence under threat, and the ability to recover from trauma [20]. Scholars from medical scientific disciplines concentrate their research on health traits, characteristics, and requirements of resilient systems that prepare mainly individuals for potential anomalies. Resilience refers to positive adaptation, or the ability to maintain or regain mental health, despite experiencing adversity [32]. Resilience can also be seen as a trait that enables an individual to recover from stressful situations and to face the next stressful situations with optimism [76].

The managerial dimension of resilience is focused on the functioning and preparedness of managed and governed systems. Resilience is mostly explained as the capacity of the system to function properly despite anomalies [17]. The nature of resilience is based on the thinking of entities, that reality must be faced with loyalty, hard work, and innovative improvised solutions, while this positive view on social reality helps people and companies to be more resilient than those with negative moods [18]. Organizational resilience, based on no duplicity of practices, tailor ability, plurality of assessment techniques, measurability, and relative ease of use, is a part of the overall management framework [57]. Building resilience must be based on strategies engaging internal and external actors in the learning process and micro-processes [8, 64].

Regarding the engineering and technological dimension of resilience, this term broadly refers to the capacity of a system to handle disruptions, failures, and surprises in ways that avoid total system collapse, while this process also leads to adaptation and improvement [43]. However, the ability of the system to recover its performance after disruption is still dominant in this field of study [11, 12].

Resilience as a multidimensional phenomenon can also be composed of different responses to crises, shocks, or threats. The practical impacts of resilience can be reflected differently in three basic types of resilience [21, 27, 63].

Precursory resilience reflects the ability of the entity to handle and manage current ongoing crises or extraordinary situations. This type includes activities focused on mitigating and preventing negative impacts, which can be achieved through risk management, crisis management, and a systematic approach. This type of resilience reflects the ability to react immediately. Recovery resilience describes the ability of the entity to recover from a crisis or extraordinary situation that has occurred. The recovery process may start during the crisis but may also be initiated after the crisis or situation. Recovery can be achieved mainly thanks to coordinated efforts and cooperation of involved stakeholders. The capacity of stakeholders and relevant entities within the networks is important. Adaptive resilience includes the ability of the entity to learn from past crises that occurred in the past. Adaptive resilience gives entities the opportunity and time to learn from mistakes and failures. Learning and capacity-building aspects of resilience must be also perceived as very important for similar crises and shocks in the future.

The topic of resilience has evolved into one of the key cross-cutting issues of contemporary society. Resilience includes dimensions and aspects connected to governmental actions and the implementation of public policies.

2.2 Resilience in Public Administration and Local Governance

The multidimensionality of resilience offers scientists a wide range of issues that are examined by different scientific disciplines. In this regard, resilience can also be examined both from the public administration and local governance perspectives.

Resilience term in the sphere of public administration is highly ambiguous, it is used for different purposes in different contexts [21, 56]. Following general explanations of resilience, the resilience of public administration is the capacity to proactively adapt to and recover from disturbances that are perceived outside the range of normal and expected disturbances [15]. In this regard, research on public administration resilience concerns different topics and issues, such as national resilience as a determinant of national security in Ukraine [7], community resilience during global pandemics [23], economic reforms in 117 countries over 11 years [12], reform of public administration in Canada [45], adaptation to the challenges of crises in Great Britain [68], Australian regional natural resource management organizations [64].

Resilience in public administration is often connected to other terms such as vulnerability, adaptation or adaptive capacity, transformability, and robustness of social entities, such as individuals, households, groups, cities and municipalities, regions, nations, or the entire global world [44]. Uncertainty, ambiguity, and complexity represent complementary perspectives that characterize resilience as a new form of neoliberal governance [34]. The growth of governmental reasoning and the defense of resilience is a logical

response to a precarious and uncertain world [53]. Resilience in public administration must be seen as a complex phenomenon and as the quality influencing different levels of government, individuals, and professions.

Communal resilience concerns processes and know-how of preparedness and planning that disperse uncertainty and responsibility for being prepared and responsible throughout the system, which acts autonomously to respond to exogenous and endogenous shocks [4, 79]. In this regard, strengthening partial aspects of communal resilience, mainly participation and inclusion, has to be seen as a key part of modern cities and municipalities and robust local democracy. Building and strengthening communal resilience is a long-term process, which implies different stakeholders in municipalities and cities [36, 52, 61].

Studies on communal resilience cover different aspects of the execution of local-self-government competencies, for example, inter-municipal collaboration in England [22], community resilience in Italian municipalities [60], urban green spaces planning for flood protection in Indonesia [1], public service delivery in South Korea metropolitan areas [36], challenges of urban resilience implications [65], resilience and management capacity during disasters at local government level [41], impact of trust in government on building community resilience in China and South Korea [37], local disaster resilience from administrative and political perspective [58], strategic implications of local resilience in England [66].

The resilience framework identifies and describes factors or components that assist them when they face crises and help them maintain their success over time [19, 71]. Theoreticians and practitioners aim to identify a resilience framework as an inspirational guide for cities, and municipalities (Table 1).

Table 1. Components of Communal Resilience

Authors	Resilience factors/dimensions/components
Buikstra et al., 2010	social networks and support, positive outlook, learning, early experiences, environment and lifestyle, infrastructure and support services, sense of purpose, diverse and innovative economy, embracing differences, beliefs, leadership
Wimelius, et al., 2018	cooperation, social networks, community resources
Torres, Alsharif, 2017	social dimension, economic development, population and governance, built environment
Tariq et al., 2021	physical, human/health, economic, environmental, social, governance
Schneider et al., 2015	infrastructure systems, social competence, community competence, economic sufficiency
Faulkner et al., 2019	exposure, sensitivity, capacity of response, adaptive capacity

(*continued*)

Table 1. (*continued*)

Authors	Resilience factors/dimensions/components
Graziano, Rizzi, 2016	openness to the external environment, structural diversification, availability of resources, structural dependence/independence, functional redundancy, adaptability strategy
Olsson et al., 2003	believes the individual´s stress, non-punitive, provisions and resources to assist, belief in the values of a society
IOM, 2019	self-esteem, social network, being flexible, a positive approach, problem-solving skills, looking after yourself
OECD, 2023	economy, society, governance, environment
City Resilience Index, 2023	leadership and strategy, health and wellbeing, economy and society, infrastructure and ecosystems
Figueiredo et al., 2018	robustness, redundancy, flexibility, resourcefulness, reflection, inclusion, integration

Source: authors

Municipalities and cities should clearly understand what needs to be done to strengthen resilience. The resilience framework concerns processes and technologies of preparedness and planning that disperse uncertainty and responsibility for being prepared throughout the system, that acts autonomously to respond to exogenous and endogenous shocks; as well as expected and unexpected risks [40, 79].

3 Methods

The study has the ambition to realize preliminary research and investigate the communal resilience framework in the Slovak Republic. The study examines measures and activities implemented by selected regional cities that strengthen communal resilience. Ahead of this analysis, the study examines, in a theoretical way, multidimensionality of the resilience, mainly focusing on communal resilience and its components.

The study aims to answer the research question what the components of the communal resilience framework are, concentrating mainly on selected regional cities in the Slovak Republic. With the use of the case study method, this study examines measures and activities for strengthening communal resilience implemented by selected regional cities in the Slovak Republic. Eight case studies from eight cities in the Slovak Republic were analyzed covering the period 2022 – 2023.

The research sample was intentionally selected (Fig. 1), taking the spatial fragmentation of the Slovak Republic and the cities' importance into consideration.

Municipalities and cities are in the Slovak Republic's conditions often perceived as initiators of innovative solutions. There are altogether eight regions in the Slovak Republic, and thus eight regional cities naturally concentrate more inhabitants than any other local self-government unit. Regional cities represent altogether more than one-fifth of the total population of the Slovak Republic. The status of a regional city is not associated with any special or unique legal status or competencies. The main difference



Fig. 1. Regional cities overview. Source: authors

between cities and other units is determined by the fact that cities realize key activities focused on the production of public services both for their residents and residents from the nearest territory. Slovakian's regional cities have even more financial, material, and human resources than small municipalities.

The case studies represent the appropriate tool, which was used to demonstrate how measures and activities implemented by regional cities strengthen communal resilience in its components. The multiple case study method helps to analyze data within each situation and across different situations, as well as to understand the similarities and differences between the cases [31, 83]. Each case study includes a description of adopted measures or activities, identification of prioritized resilience dimension by selected cities, impact of the implemented solution on communal resilience, and components necessary for the successful implementation of the measures.

A literature review was used to integrate findings and perspectives from empirical findings. Previous research from different scientific disciplines was investigated to demonstrate the contemporary state of knowledge in the sphere of resilience, mainly communal resilience.

Theoretical analysis was used to analyze the contemporary state of research focusing on the concept of resilience, mainly communal resilience. Content analysis was used to get an in-depth view of relevant activities of the selected regional cities. Abstraction was used in the context of filtering those aspects of selected cases, which were relevant to our research and communal resilience framework. The method of synthesis was used to systematize new ideas based on our research, as well as to draw conclusions resulting from the analysis.

4 Results

The following case studies demonstrate activities strengthening resilience in selected cities. Each of the eight case studies includes a description of adopted measures or activities, identification of prioritized resilience dimension by selected cities, impact of the implemented solution on communal resilience, and components necessary for the successful implementation of the measures.

4.1 Strengthening of Energy Independence

The city of Trnava belongs to the leaders in energy independence among Slovak cities. Between 2022 and 2023, Trnava implemented innovative solutions based on the installation of photovoltaic devices on the roofs of elementary schools established by the city. The solution was realized mainly thanks to positive previous experience in the city, production of own electricity from photovoltaic devices on the roofs of elementary schools, and health and social facilities. The implementation of these solutions resulted in the reduction of carbon footprint by 252 tons of CO2, an average of 67% of cost saving of electricity costs for one school, and also supply of pre-flow electricity to the network that was used by the Ice Stadium of Trnava [75].

The identified solution implemented by the city of Trnava highlights mainly energy independence which is a key aspect of preparedness for future crises. However, financial effectiveness was achieved already at the time of project implementation. Simultaneously, the chosen solution is also environmentally friendly.

4.2 Digitalization and Circular Economy

The city of Nitra included the topic of resilience also to the vision of the city. This ambition is complemented by the support of the city to implement activities in the sphere of circular and shared local economy. The functioning of local circular and shared local economy is thanks to the interactive Circular map of Nitra smoother and healthier. An interactive map helps citizens to find different goods and services in the city. The circular map of Nitra provides information on different parts of the circular and shared economy in the city, for example, car and bike-sharing, services and repair shops, community gardens, compost sites, packaging-free stores, swap markets, collection yards, containers for small electrical waste and used clothing, as well as events focused on ecological activities and many others [47].

The case of resilient activity implemented by the management of the city of Nitra covers components of resilience. Firstly, the selected solution strengthens networking among communities in the city, which can be very useful not just in the time of unexpected crisis, but also in the time of any disturbance from normal life. The circular map also builds awareness of the circular economy and the need to reduce waste. The secondary impacts of the presented solution can be seen mainly in the environmental protection and reusing habits of citizens.

4.3 Unique Mobile Application for Increased Safety

The resilience of the city of Prešov was strengthened thanks to the unique mobile application. The solution adopted by the city was the first of its kind among municipalities in the Slovak Republic. The similar mobile app is currently used only by the Mountain Rescue Service and Air Rescue Service. Platform “Safety” allows the use of multimedia communication to be added to the standard emergency call. After the initialization of the emergency call, the individual will receive an SMS message with a specific link from the operator of the emergency center. When individuals open this link, they confirm sharing

their location and start a video call after allowing access to the phone´s camera. The platform also includes a chat with the possibility of translation to 30 languages [51].

The solution adopted by the city of Prešov reflects the ambition of the city to strengthen the safety of citizens in an emergency or crisis. The mobile application represents a user-friendly solution that helps citizens protect their properties and their lives in times of natural and man-made emergencies. Application is also inclusive, because the benefits of application can be perceived by different types of groups regardless of age, education, or social status, and without previous registration or authorization. However, previous coordination of emergency services departments is more than necessary, which needs a systematic approach by the city´s management.

4.4 Systematic Evaluation as a Tool for Strong Communities

Banská Bystrica realizes different types of activities funded by different projects, funded by European, national, and own financial resources. Measures focused on strengthening resilience have helped the city to react to climate change, support green and blue infrastructure, engage local communities in participatory budgeting, revitalize public spaces, as well as to develop sustainable mobility in the functional city region [5]. Systematic evaluation and complementary implementation of partial activities help the city not just to achieve the goals of the projects, but also to create a resilient environment with the involvement of relevant stakeholders.

The identified case represents the ambition of the city to strengthen resilience through the ecological dimension, with a secondary positive impact on the quality of life and health of citizens. The management of the city also fosters the involvement of relevant communities, supporting their accountability for the future of the environment. Implemented activities are evaluated and presented every year, which can be seen as a planned and systematic approach guaranteed by the city´s office.

4.5 Preparedness for Climate Change in Communal Life

Activities focused mainly on environmental aspects of resilience are being implemented in the city of Žilina. However, these activities have different cross-sectional impacts on citizens´ quality of life. In the summer of 2023, Žilina adopted a Strategy and action plan for adaptation to the adverse consequences of climate change in the territory of the city of Žilina, which helps the city effectively implement measures raising preparedness for climate change safely and timely, and thus ensure sustainable and resilient functioning of the city in the future [85]. The strategic approach of the city helps to systematize activities focused on environmental resilience in different spheres of communal life, such as planting linear and mobile greenery, revitalization of city parks, support of electromobility, as well as reduction of energy consumption and building of green roofs at city´s buildings [84].

Environmental aspects of resilience are strengthened by activities of the city of Žilina. Mentioned activities are defined also by the strategies of the city. Activities aim to improve and enhance the green and blue environment surrounding citizens, mainly to improve quality of life and decrease the financial costs of the city´s facilities.

4.6 Green and Living Housing Estates

Activities reflecting community and ecological aspects of resilience were realized in the Karlova Ves, city district of the city of Bratislava, the capital of Slovakia. These activities were a part of the DELIVER project implemented between 2018–2023. The main aim of the activities was to strengthen the resilience of the housing estates to the impact of climate change, mainly because of the balanced spectrum of measures. The project aimed to turn housing estates into climate-resilient living places through the project activities, such as building awareness on climate resilience and carbon footprint, using of integrated approach in adaptation and mitigation measures, increasing participation of the public, and suggesting changes in legislation [35]. The importance of resilience was also supported by subjects from private and non-governmental sectors.

The resilience of communities and the strong involvement of stakeholders were identified in the case of the Karlova Ves. Communities and strong networking have an important role in measures that aim to foster climate-resilient housing estates. Simultaneously, activities help to increase the quality of life and health protection processes.

4.7 Strategy with Clear Measures, Timeline, and Responsibility

The city of Košice has decided to manage partial aspects of resilience systematically. In this regard, the priorities connected with resilience are declared by a binding document The economic and social development plan of the city of Košice and its function area 2022–2027. The mentioned strategy includes 21 goals with significant importance for the current city management. Among other important spheres of communal life, Košice aims to increase the city's resilience to extraordinary events through effective risk management. Strategy precisely describes measures, specifically measures on prevention of extraordinary situations focusing on the protection of life, health, and property and mitigation of negative impacts of these situations, development, renewal, and strengthening of technical and logistic capacities including management, rescue units, and self-government units, improving the preparedness of public in the sphere of civil protection [39]. Strategy also defines timeline, financial resources, and responsibility for the realization of the identified measures.

The city of Košice has chosen to systematically coordinate measures that strengthen resilience. The main development strategy of the city precisely describes particular activities and implementation processes. This approach of the city leads to a higher quality of realized activities, creates an adequate informational base for citizens and other stakeholders, and rationally uses personal, material, and financial resources.

4.8 Long-Term Visions by European Values

Trenčín city management perceives resilience as a preparedness for extraordinary situations and climate change but with a focus on the environmental aspect of examined phenomena. The city also uses a systematic approach and includes resilience measures into a strategic document called the Program of Economic Development and Social Development of the City of Trenčín for the years 2023–2029 with a view to 2050. The mentioned strategy includes resilience measures in connection to selected spheres of

life, mainly environment and renewable resources, rural development, and green and blue infrastructure [74]. Measures are focused on the building of awareness, informational support, and free-time activities that reflect the development of a low-carbon economy, effective use of resources, adaptation to climate change, and preparedness for extraordinary situations.

A long-term vision on the topic of resilience was identified in the case of the city of Trenčín. The main strategy of the city defines priorities for the seven-year horizon but also declares the required development of partial spheres of life with a view to 2050. This long-term vision reflects the aims and goals of similar documents adopted at the national or European level. A similar long-term approach is unique in cities and municipalities but confirms the importance of a strategy approach.

5 Discussion

Resilience has become a frequently discussed issue in the sphere of public administration and local self-government. As demonstrated by the previous research, resilience can be improved and that is the main justification for studies that aim to investigate its components. The mentioned research and selected case studies demonstrated that communal resilience can be decomposed into partial components (Fig. 2).

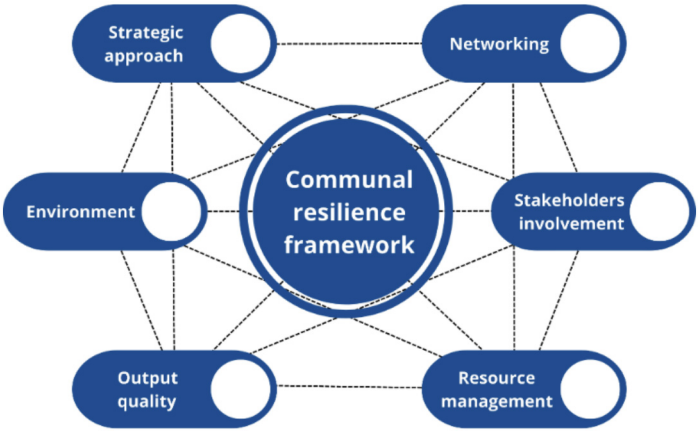


Fig. 2. Communal resilience framework. Source: authors.

A strategic approach must be seen as the first and most crucial component of the communal resilience framework. Cities and municipalities usually adopt different types of documents, strategies, and action plans. Some of them are required by the national legislation, but cities and municipalities also adopt documents at their own decision. Currently, there is no legal obligation to adopt a document focused on resilience. At the communal level, two types of approaches can be identified. Cities and municipalities often elaborate documents focused mainly on ecological and energetic dimensions of resilience. Simultaneously, the topic of resilience is very often incorporated in different

types of documents, while the same partial components of resilience can be found in two or more documents.

As was proven by the theory and case studies, networking and increasing the capacity of social networks is a very important component of communal resilience. Cities and municipalities should proactively strengthen mutual social connections between entities in their territory. Different communities can positively influence the ability of cities and municipalities to prepare, respond, adapt, and recover from crises and extraordinary situations. Communities that may be perceived as distant may be the source of success, for example, volunteers, youth, seniors, and people with disabilities. Vital social networks help local democracy to take advantage of adequate responses when it is needed. Strong communities may help cities to be more resilient and also may help cities to provide public goods and services on a complementary basis, not just in normal situations, but also in times of crisis or emergency.

Stakeholders' involvement is a key part of successful policymaking in each sphere of life. The involvement of relevant stakeholders in the planning and implementation of partial activities may increase the capacity of cities and municipalities to be more resilient. Transparency and openness of these processes help stakeholders not only to gather necessary information but also to communicate with cities and municipalities through official and approved channels. Awareness of stakeholders on their roles and accountability during the crisis is an important precondition for the successful management of disturbances in communal life. Involved communities can also help cities and municipalities to achieve outcomes of public policies with lower costs.

Resource management is in the context of resilience mostly perceived as economic effectiveness and cost saving. This view mainly results from the saving of public finances generated by green and digital technologies adopted by cities and municipalities. In this regard, economic effectiveness has the potential to strengthen resilience, and vice versa. However, measures focused on strengthening communal resilience also save other types of resources, mainly material and personal of cities and municipalities. Thus, it can be mutually beneficial to use the potential of communities to innovate and critically evaluate public services and communal life needs. Part of this component is also decreasing of energy consumption of facilities and energy independence and security.

Output quality represents mainly the quality of public goods and services provided by cities and municipalities. Besides, it can be also perceived as the quality of resilience that can be compared between local self-government units. In this regard, this component includes the quality of partial public services that strengthen resilience, but also the quality of communal resilience established by the city´s management and co-created by involved stakeholders. Finally, this component also influences the quality of life perceived by citizens.

Environment as another component of the communal resilience framework reflects the importance of resilience in the sphere of ecology. Practical implications represent mainly climate change management, expansion and maintenance of greenery, and biodiversity, as well as the development of green and blue infrastructure. The importance of this component is also underlined by the growing rate of natural disasters and the building of awareness on the protection of the environment. The environment surrounds each human activity, thus the quality of the environment affects a wide range of competencies

performed by cities and municipalities, as well as the everyday activities of citizens. It is easy to harm nature and the environment, but it takes much longer to repair that damage. In this regard, the environmental dimension must be perceived as an important part of strategies and visions in the conditions of cities and municipalities.

The results showed that analyzed regional cities in Slovakia have different approaches to the topic of resilience. Selected cities concentrate their attention on identified components. Table 2 includes a comprehensive summarization of analyzed cases focusing on the occurrence of partial components of the communal resilience framework.

Table 2. Comprehensive summarization of communal resilience components

	Strategic approach	Networking	Stakeholder involvement	Resource management	Output Quality	Environment
Case 1 Strengthening of Energy Independence	x			x	x	x
Case 2 Digitalization and Circular Economy		x	x	x		x
Case 3 Unique mobile application for increased safety	x				x	
Case 4 Systematic evaluation as a tool for strong communities	x	x	x		x	x
Case 5 Preparedness for climate change in communal life	x	x	x			x
Case 6 Green and living housing estates		x	x		x	x

(*continued*)

Table 2. (*continued*)

	Strategic approach	Networking	Stakeholder involvement	Resource management	Output Quality	Environment
Case 7 Strategy with clear measures, timeline, and responsibility	x	x	x	x		
Case 8 Long-term visions by European values	x		x			x

Source: authors

Cities, and especially bigger cities, have an important role in strengthening and improving communal resilience. With their infrastructure and resources, bigger cities can provide help and assistance to smaller municipalities in the nearest surroundings. The developed communal resilience framework applies not only to the city itself, but also to functional urban and metropolitan regions, or any other communal units. Especially bigger cities have the potential to serve as an entity that smaller cities and municipalities can rely on in times of crisis or emergency. Small municipalities may not always be able to be resilient in crises, therefore those municipalities may rely on bigger (region) cities that have enough financial, personnel, and human capacities.

6 Conclusion

The topic of resilience has evolved into a crucial phenomenon that is gaining more and more attention from theoreticians and practitioners. This tendency is even more visible in the local self-government, a part of public administration that directly affects the quality of life. Based on previous research, resilience, and communal resilience refer to the ability of local self-government units to react, adapt, and recover from expected and unexpected crises or emergencies. In this regard, the communal resilience framework defines components of preparedness and planning that help local self-government units resolve crises or emergencies caused by endogenous and exogenous factors.

Based on the literature review and presented case studies, six complementary components of the communal resilience framework have been identified, specifically strategic approach, networking, stakeholder involvement, resource management, output quality, and environment. The main benefit of the developed communal resilience framework is its applicability not just for cities, but the framework is also applicable by functional urban and metropolitan regions, or any other communal units. Simultaneously the study contributes to the growing discussion on the standardization of communal resilience framework. The importance of research is also underlined by the increasing rate of

crisis and emergencies, that constantly challenge cities and municipalities across the world. Despite the benefits of the study, there are still limitations to be addressed in further research. First, our findings were partially based on the intentional selection of case studies. Nevertheless, we consider their information value sufficient to demonstrate different aspects of communal resilience. Our research can be further extended from the following aspects, mainly broadening the empirical evidence, and further analysis of different approaches to resilience across municipalities, cities, regions, and governments.

Acknowledgments. The article is created as a result of a project supported by the Scientific Grant agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic and the Slovak Academy of Sciences, Grant no: 1/0734/22.

References

1. Afriyanie, D., Julian, M.M., Riqqi, A., Akbar, R., Suroso, D.S.A., Kustiwan, I.: Re-framing urban green spaces planning for flood protection through socio-ecological resilience in Bandung City, Indonesia. Cities **101**, 102710 (2020). https://doi.org/10.1016/j.cities.2020.102710
2. Allen, C.R., Cumming, G.S., Garmestani, A.S., Taylor, P.D., Walker, B.H.: Managing for resilience. Wildl. Biol. **17**(4), 337–349 (2011). https://doi.org/10.2981/10-084
3. Angeler, D.G., Allen, C.R.: Quantifying resilience. J. Appl. Ecol. **53**, 617–624 (2016). https://doi.org/10.1111/1365-2664.12649
4. Baibarac, C., Petrescu, D.: Co-design and urban resilience: visioning tools for commoning resilience practices. CoDesign **15**(2), 91–109 (2019). https://doi.org/10.1080/15710882.2017.1399145
5. Bystrica, B.: Information about the current activities of the city of Banská Bystrica in the area of the environment. https://cdn.banskabystrica.sk/2022/09/Informacia-o-aktualnych-aktivitach-mesta-Banska-Bystrica-v-oblasti-zivotneho-prostredia-31.8.2022-MsZ.pdf. Accessed 07 Feb 2024
6. Birkie, S.E., Truco, P., Campos, P.F.: Effectiveness of resilience capabilities in mitigating disruptions: leveraging on supply chain structural complexity. Supply Chain Manag. **22**(6), 506–521 (2017). https://doi.org/10.1108/SCM-01-2017-0009
7. Bondarenko, S., Tkach, I., Drobotov, S., Mysyk, A., Plutytska, K.: National resilience as a determinant of national security of Ukraine. J. Optim. Ind. Eng. **14**(Special Issue), 87–93 (2021) https://doi.org/10.22094/JOIE.2020.677837
8. Branicki, L., Steyer, V., Sullivan-Taylor, B.: Why resilience managers aren't resilient, and what human resource management can do about it. Int. J. Hum. Resour. Manag. **30**(8), 1261–1286 (2016). https://doi.org/10.1080/09585192.2016.1244104
9. Bristow, G., Healy, A.: Crisis response, choice and resilience: insights from complexity thinking. Camb. J. Reg. Econ. Soc. **8**(2), 241–256 (2015). https://doi.org/10.1093/cjres/rsv002
10. Buikstra, E., et al.: The Components of resilience - perceptions of an Australian rural community. J. Community Psychol. **38**(8), 975–991 (2010). https://doi.org/10.1002/jcop.20409
11. Cassottana, B., Shen, L., Ching Tang, L. C.: Modeling the recovery process: a key dimension of resilience. Reliab. Eng. Syst. Saf. **190** 106528 (2019) https://doi.org/10.1016/j.ress.2019.106528
12. Castañeda, G., Guerrero, O.A.: The resilience of public policies in economic development. Public Policy Model. Appl. **2018**, 9672849 (2018). https://doi.org/10.1155/2018/9672849

13. City Resilience Index. https://www.cityresilienceindex.org/#/city-profiles. Accessed 02 Feb 2024
14. City Resilience Index.: CRI Brochure: Understanding and measuring City Resilience, https://www.dropbox.com/s/ah846bs4a6609ce/C6%20-%20CRI%20Brochure.pdf?dl=0. Accessed 02 Dec 2024
15. Comfort, L.K., Boin, A., Demchak, C.C. (eds.): Designing Resilience: Preparing for Extreme Events. University of Pittsburgh Press (2010). https://doi.org/10.2307/j.ctt5hjq0c
16. Comin, D.A., Cruz, M., Cirera, X., Lee, K.M, Torres, J.: Technology and Resilience. NBER Working Papers No. 29644 (2022) https://doi.org/10.3386/w29644
17. Comoretto, A.: Processes of Resilience Development in a Population of Humanitarian Aid Workers. In: Bharma, R. (ed.) Organizational Resilience: Concepts, Integration, and Practice, pp. 47–66. CRC Press, Boca Raton (2016)
18. Coutu, D.L.: How Resilience Works. Harvard Bus. Rev. **80**(5), 46–55 (2002)
19. Cretney, R. M.: Local responses to disaster: the value of community led post disaster response action in a resilience framework. Disaster Prev. Manag. **25**(1), 27-40 (2016) https://doi.org/10.1108/DPM-02-2015-0043
20. De Tychey, C., Lighezzolo-Alnot, J., Claudon, P., Garnier, S., Demogeot, N.: Resilience, mentalization, and the development tutor: a psychoanalytic and projective approach. Rorschachiana **33**(1), 49–77 (2012). https://doi.org/10.1027/1192-5604/a000027
21. Duit, A.: Resilience thinking: lessons for public administration. Public Adm. **94**(2), 364–380 (2016). https://doi.org/10.1111/padm.12182
22. Elston, T., Bel, G.: Does inter-municipal collaboration improve public service resilience? Evidence from local authorities in England. Public Manag. Rev. **25**(4), 734–761 (2022). https://doi.org/10.1080/14719037.2021.2012377
23. Entress, R.M., Tyler, J., Sadiq, A.: Managing mass fatalities during COVID-19: lessons for promoting community resilience during global pandemics. Public Adm. Rev. **80**(5), 856–861 (2020). https://doi.org/10.1111/puar.13232
24. European Commission.: Resilience. https://joint-research-centre.ec.europa.eu/scientific-activities-z/resilience_en. Accessed 02 Feb 2024
25. Faulkner, J.P., Murphy, E., Scott, M.: Developing a holistic 'vulnerability-resilience' model for local and regional development. Eur. Plan. Stud. **28**(12), 2330–2347 (2020). https://doi.org/10.1080/09654313.2020.1720612
26. Figueiredo, L., Honiden, T., Schumann, A.: Indicators for Resilient Cities. OECD Regional Development Working Papers 2018/02, (2018). https://doi.org/10.1787/6f1f6065-en
27. FitzGerald, C., Hameed, T., Rosenbach, F., Ruairi, J., Macdonald, J., Dixon, R.: Resilience in public service partnerships: evidence from the UK life chances fund. Public Manag. Rev. **25**(4), 787–807 (2023). https://doi.org/10.1080/14719037.2021.2015186
28. Folke, C.: Resilience (republished). Ecol. Soc. **21**(4) Article 44 (2016). https://doi.org/10.5751/ES-09088-210444
29. Fraccascia, L., Giannoccaro, I., Albino, V.: Resilience of complex systems: state of the art and directions for future research. Complexity **2018**, 1–44 (2018). https://doi.org/10.1155/2018/3421529
30. Graziano, P., Rizzi, P.: Vulnerability and resilience in the local systems: the case of Italian provinces. Sci. Total. Environ. **553**, 211–222 (2016). https://doi.org/10.1016/j.scitotenv.2016.02.051
31. Gustafsson, J.: Single case studies vs. multiple case studies: A comparative study, https://hh.diva-portal.org/smash/get/diva2:1064378/FULLTEXT01.pdf. Accessed 03 Mar 2024
32. Herrman, H., Stewart, D.E., Diaz-Granados, N., Berger, E.L., Jackson, B., Yuen, T.: What is Resilience. Can. J. Psychiatry **56**(5), 258–265 (2011). https://doi.org/10.1177/070674371105600504

33. International Organization for Migration. What Is Resilience?, https://www.iom.int/sites/g/files/tmzbdl486/files/staff-welfare/resilience.pdf. Accessed 02 Jan 2024
34. Juncos, A.E.: Resilience in peacebuilding: Contesting uncertainty, ambiguity, and complexity. Contemp. Secur. Policy **39**(4), 559–574 (2018). https://doi.org/10.1080/13523260.2018.1491742
35. Ves, K.: Resilient housing estates, https://odolnesidliska.sk/o-projekte/. Accessed 02 Feb 2024
36. Kim, K., Andrew, S.A., Jung, K.: Building resilient organizations: organizational resilience as a network outcome. Int. J. Public Adm. **44**(15), 1319–1328 (2020). https://doi.org/10.1080/01900692.2020.1758720
37. Kim, S.: Public trust in government in China and South Korea: implications for building community resilience. Chin. Public Adm. Rev. **7**(1), 35–76 (2022). https://doi.org/10.22140/cpar.v7i1.118
38. Kiss, T., Kiss, V.M.: Develop resilience - a System-level dynamic indicator for testing the long-term impact of planned projects based on a watershed and a city strategy example. Ecol. Indic. **129**, 107970 (2021). https://doi.org/10.1016/j.ecolind.2021.107970
39. Košice.: Program of economic development and social development of the city of Košice and its function area 2022–2027: Action plan for the development of the city of Košice 2022–2024. https://static.kosice.sk/files/manual/phsr/Akcny_plan_rozvoja_mesta_Kosice_2022-2024.pdf. Accessed 02 Feb 2024
40. Labaka, L., Maraña, P., Giménez, R., Hernantes, J.: Defining the roadmap towards city resilience. Technol. Forecast. Soc. Chang. **146**(2019), 281–296 (2019). https://doi.org/10.1016/j.techfore.2019.05.019
41. Lee, D.: Local government's disaster management capacity and disaster resilience. Local Gov. Stud. **45**(6), 803–826 (2019). https://doi.org/10.1080/03003930.2019.1653284
42. LNCS Homepage. http://www.springer.com/lncs. Accessed 25 Oct 2023
43. Macrae, C.: Moments of Resilience: Time, Space and the Organisation of Safety in Complex Sociotechnical Systems. In: Wiig, S., Fahlbruch, B. (eds.) Exploring Resilience: A Scientific Journey from Practice to Theory, pp. 15–23. Springer International Publishing, Cham (2019). https://doi.org/10.1007/978-3-030-03189-3_3
44. Martin-Breen, P., Anderies, J.M.: Resilience: A Literature Review. Bellagio Initiative, Brighton (2011)
45. Milley, P., Jiwani, F.: Resilience and public administration: Implications for the "New Political Governance" in Canada. In: Ionescu, S., Tomita, M., Cace, S. (eds.) The Second World Congress on Resilience: From Person to Society, pp. 803–808. MEDIMOMD, Bologna (2014)
46. National Ocean Service.: What is resilience? https://oceanservice.noaa.gov/facts/resilience.html. Accessed 02 Jan 2024
47. Nitra.: Circular map – Nitra. https://www.google.com/maps/d/u/0/viewer?mid=1a6X15sk5IZ-tHZvFcPGr0ku6jRKmW21R&ll=48.2848307%2C18.07445600000002&z=11. Accessed 02 Feb 2024
48. OECD.: Resilience. https://www.oecd.org/naec/projects/resilience/. Accessed 25 Oct 2025
49. OECD.: Resilient Cities. https://www.oecd.org/fr/gov/politique-regionale/resilient-cities.htm. Accessed 25 Oct 2023
50. Olsson, G.A., Bond, L., Burns, J.M., Vella-Brodrick, D.A., Sawyer, S.M.: Adolescent resilience: a concept analysis. J. Adolesc. **26**(1), 1–11 (2003). https://doi.org/10.1016/S0140-1971(02)00118-5
51. Prešov.: Prešov has a unique application for greater safety of citizens. https://www.presov.sk/presov-ma-unikatnu-aplikaciu-pre-vacsiu-bezpecnost-obcanov-oznam/mid/491237/.html#m_491237. Accessed 07 Feb 2024
52. Alina Georgiana, P., Corina-Cristiana, N.: What strengthens resilience in public administration institutions? Eastern J. Eur. Stud. **12**(Special issue), 100–125 (2021). https://doi.org/10.47743/ejes-2021-SI05

53. Pugh, J.: Resilience, complexity and post-liberalism. Area **46**(3), 313–319 (2014). https://doi.org/10.1111/area.12118
54. Punzo, G., et al.: Engineering resilient complex systems: the necessary shift toward complexity science. IEEE Syst. J. **14**(3), 3865–3874 (2020). https://doi.org/10.1109/jsyst.2019.2958829
55. Rana, I.A.: Disaster and climate change resilience: a bibliometric analysis. Int. J. Disaster Risk Reduction **50**, 101839 (2020). https://doi.org/10.1016/j.ijdrr.2020.101839
56. Reid, R., Courtenay Botterill, L.: The multiple meanings of 'resilience': an overview of the literature. Aust. J. Public Adm. **72**(1), 31–40 (2016). https://doi.org/10.1111/1467-8500.12009
57. Rød, B., Lange, D., Theocharidou, M., Pursiainen, Ch.: From risk management to resilience management in critical infrastructure. J. Manag. Eng. **36**(4) (2020). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000795
58. Ross, A.D.: Local Disaster Resilience: Administrative and Political Perspectives. Routledge, New York (2014)
59. Rutter, M.: Resilience as a dynamic concept. Dev. Psychopathol. **24**(2), 335–344 (2012). https://doi.org/10.1017/S0954579412000028
60. Sampugnaro, R., Santoro, P.: The pandemic crisis, Italian municipalities, and community resilience. Partecipazione & Conflitto, **14**(Special Issue), 283–301 (2021). https://doi.org/10.1285/i20356609v14i1p283
61. Sarker, M.N.I., Min, W., Shouse, R.C., Ma, C.: Administrative Resilience and Adaptive Capacity of Administrative System: A Critical Conceptual Review. In: Jiuping, X., Ahmed, S.E., Cooke, F.L., Duca, G. (eds.) Proceedings of the Thirteenth International Conference on Management Science and Engineering Management: Volume 2, pp. 717–729. Springer International Publishing, Cham (2020). https://doi.org/10.1007/978-3-030-21255-1_55
62. Schneider, J., Romanowski, C., Raj, R.K., Mishra, S., Stein, K.: Measurement of locality specific resilience. In: 2015 IEEE International Symposium on Technologies for Homeland Security (HST). Institute of Electrical and Electronics Engineers, Boston, pp.1–6 (2015) https://doi.org/10.1109/THS.2015.7225332
63. Schulman, P., Roe, E.: Reliability and Risk: The Challenge of Managing Interconnected Infrastructures. Stanford University Press (2016). https://doi.org/10.11126/stanford/9780804793933.001.0001
64. Sellberg, M.M., Ryan, P., Borgström, S.T., Norström, A.V., Peterson, A.V.: From resilience thinking to resilience planning: lessons from practice. J. Environ. Manage. **217**(2018), 906–918 (2018). https://doi.org/10.1016/j.jenvman.2018.04.012
65. Shamsuddin, S.: Resilience resistance: the challenges and implications of urban resilience implementation. Cities **103**, 102763 (2020). https://doi.org/10.1016/j.cities.2020.102763
66. Shaw, K., Maythorne, L.: Managing for local resilience: towards a strategic approach. Public Policy Adm. **28**(1), 43–65 (2012). https://doi.org/10.1177/0952076711432578
67. Somers, S.: Measuring resilience potential: an adaptive strategy for organizational crisis planning. J. Contingencies Crisis Manag. **17**(1), 12–23 (2009). https://doi.org/10.1111/j.1468-5973.2009.00558.x
68. Stark, A.: Bureaucratic values and resilience: an exploration of crisis management adaptation. Public Adm. **92**(3), 692–706 (2014). https://doi.org/10.1111/padm.12085
69. Tanner, T., Bahadur, A., Moench, M.: Challenges for resilience policy and practice. https://odi.cdn.ngo/media/documents/11733.pdf. Accessed 02 Jan 2024
70. Tariq, H., Pathirage, C., Fernando, T.: Measuring community disaster resilience at local levels: an adaptable resilience framework. Int. J. Disaster Risk Reduction **62**, 102358 (2021). https://doi.org/10.1016/j.ijdrr.2021.102358
71. Tengblad, S., Oudhuis, M. (eds.): The Resilience Framework: Organizing for Sustained Viability. Springer Singapore, Singapore (2018)

72. Tudor, Ţ, Cristina, H., Bianca, A.: Adaptive and turbulent governance. ways of governing that foster resilience. the case of the COVID-19 pandemic. Transylvanian Rev. Adm. Sci. **16**(Special Issue 2020), 167–182 (2020). https://doi.org/10.24193/tras.SI2020.10
73. Torres, H., Alsharif, K.: What it means to become "more resilient": an analysis of local resilience-building approaches in three Florida communities. Weather, Clim. Soc. **9**, 405–419 (2017). https://doi.org/10.1175/WCAS-D-16-0101.1
74. Trenčín.: Program of economic development and social development of the city of Trenčín for the years 2023–2029 with a view to 2050. https://trencin.sk/wp-content/uploads/2023/01/Program-hospodárskeho-rozvoja-a-sociálneho-rozvoja-mesta-Trenčín-na-roky-2023-2029.pdf. Accessed 02 Feb 2024
75. Trnava.: The city of Trnava is as the leader of energy independence. https://www.trnava.sk/sk/aktualita/mesto-trnava-na-cele-v-oblasti-energetickej-samostatnosti. Accessed 02 Feb 2024
76. Van Schrojenstein Lantman, M., et al.: Mental resilience, perceived immune functioning, and health. J. Multi. Healthc. 10 (2017), 107-112 (2017). https://doi.org/10.2147/JMDH.S130432
77. VanMeter, F., Cicchetti, D.: Resilience. In: Neurocognitive Development: Normative Development, pp. 67–73. Elsevier (2020). https://doi.org/10.1016/B978-0-444-64150-2.00008-3
78. Walker, B.: Resilience: what it is and is not. Ecol. Soc. **25**(2), 11 (2020). https://doi.org/10.5751/ES-11647-250211
79. Welsh, M.: Resilience and responsibility: governing uncertainty in a complex world. Geogr. J. **180**(1), 15–26 (2014). https://doi.org/10.1111/geoj.12012
80. Wimelius, M.E., Eriksson, M., Kinsman, J., Strandh, V., Ghazinour, M.: What is local resilience against radicalization and how can it be promoted? A Multi. Lit. Rev. **46**(7), 1108–1125 (2023). https://doi.org/10.1080/1057610X.2018.1531532
81. Woods, D. D.: Essential characteristics of resilience. In: Hollnagel, E., Woods, D.D., Leveson, N. (eds.) Resilience engineering: Concepts and Precepts. CRC Press, London, pp. 21–34 (2017). https://doi.org/10.1201/9781315605685
82. Wukich, C.: Searching for resilience. J. Public Adm. Res. Theory **23**(4), 1013–1019 (2013). https://doi.org/10.1093/jopart/mut034
83. Yin, R.K.: Case Study Research Design and Methods. SAGE Publications, Thousand Oaks (2018)
84. Žilina.: Mitigation and adaptation to climate change in the city of Žilina, https://www.zilinaklima.sk/o-projekte/#. Accessed 07 Feb 2024
85. Žilina.: Strategy and action plan for adaptation to harmful consequences of climate change in the territory of the city of Žilina. https://zilina.sk/wp-content/uploads/2023/10/26.-Adaptacny-plan-zmena-klimy.pdf. Accessed 07 Feb 2024

Coastal Land Use Planning. An Integrated Approach Between Environmental Protection, Economic Competition and National Defense

The Case of Quirra, Sardinia (Italy)

Nicolò Fenu[1,2(✉)], Ginevra Balletto[3], and Giuseppe Borruso[4]

[1] ESOMAS - Department of Economics, Social Studies, Applied Mathematics and Statistics, University of Turin, Turin, Italy
nicolo.fenu@unito.it
[2] Sardarch Spin off University of Cagliari, Cagliari, Italy
[3] DICAAR - Department of Civil, Environmental Engineering and Architecture, University of Cagliari, Cagliari, Italy
balletto@unica.it
[4] DEAMS - Department of Economics, Business, Mathematics and Statistics "Bruno de Finetti", University of Trieste, Trieste, Italy
giuseppe.borruso@deams.units.it

Abstract. The integrated management of marine and coastal areas is considered one of the main components of the concept of sustainable development, capable of increasing the well-being of coastal communities and maintaining ecological integrity and biological diversity. In particular, Chapter 17 of Agenda 21 (UN 1992) relating to the protection of the oceans, all types of seas including closed and semi-enclosed seas and coastal areas and the protection, rational use and valorisation of their living resources, directs towards new integrated management approaches of coastal areas at different scales, through interdisciplinary, participatory and responsible methods and tools. The marine environment, including adjacent coastal areas, therefore, constitutes an essential component of the global life support system, offering sustainable development opportunities for communities. This is contrasted by extensive technical and scientific literature, which contributes to forming the "right to the sea", understood as the right to freely enjoy the sea and the beaches according to the "common good" approach. Specifically, the Autonomous Region of Sardinia recognized the Coastal Land Use Plan (PUL) as the main implementation tool through which the Municipalities, within the framework of the powers conferred pursuant to Article 41 of the Regional Law. 9/2006 (Conferral of functions and tasks to local authorities) can plan in the Maritime State Property for tourist-recreational purposes. The present manuscript is inserted into this concise framework, with which it is intended to represent the integrated and systemic approach conducted by the authors for the drafting of the PUL of the Municipality of Villaputzu (Sardinia, Italy) between environmental protection, economic competition and national defense.

Keywords: Coastal Land Use Planning · Integrated Coastal Planning · Sardinia (Italy)

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 131–140, 2024.
https://doi.org/10.1007/978-3-031-65238-7_9

1 Introduction

The Italian territory covers about 35% of the European continent, with 4,921 bathing sites out of 13,741 European countries [17]. The bathing marine coastline represents 66.5% of the total length of the Italian coast [12].

With Council of Europe Resolution No. (73) 29 of October 26, 1973, integrated coastal zone management has been given increasing prominence within the theoretical scientific-planning debate, so much so that it has been placed at the center of European spatial policies. Specifically, integrated management involves an approach that succinctly includes data collection and interoperability, the active participation of the various actors involved, and the development of consonant policies [13, 15] designed to enhance the well-being of coastal communities and maintain ecological integrity and diversity.

In particular, Chapter 17 of Agenda 21 [24] on the protection of oceans, seas (including enclosed and semi-enclosed), and coastal zones, directs toward new integrated management approaches at different scales through interdisciplinary, participatory, and accountable methods and tools [18]. The marine environment, including adjacent coastal areas, is confirmed as an essential component of the global life-support system, providing sustainable development opportunities for communities.

The International Law of Coastal States [25] provides the main elements for protecting and conserving the marine and coastal environment and its resources. Anthropogenic and natural changes are the focus of the most recent international policies to accelerate the ecological, digital, and energy transition. These require new integrated approaches, including strengthening cooperation among institutions [26] for sustainable management of the marine-coastal environment and for reconciling use with climate change. Integrated coastal zone management/planning is a tool recognized in European environmental legislation for pursuing economic, social and environmental sustainability [20], resulting in the containment of impacts from the interaction between marine and terrestrial uses [22].

Coastal planning in Italy remains highly contradictory and fragmented due to the division of responsibilities among the state, regions, and municipalities. Law No. 979 of December 31, 1982, which mandated a "General Merchant Plan for the Defense of the Sea and Coasts," drafted by the Ministry of the Navy in cooperation with the regions, was supposed to represent a significant shift in marine and coastal environmental protection policies. However, the establishment of marine reserves, as stipulated in the law, has made gradual progress, even though the actual management of these areas remains challenging. Regarding the coastal land area, beyond the generic designation of the first 300 m as a landscape-protected zone, as established by the Galasso Decree, Italy lacks proactive protection guidelines or measures to counter the increasing pressure to transform coastal land, unlike in other countries. The progressive occupation of the maritime domain is further complicated by the absence of effective management criteria that protect public use and sensitive areas. Recent changes to the legal framework, transferring primary coastal responsibilities from the state to the regions, position the regional level as optimal for implementing integrated coastal planning and management policies.

Moreover, the issue of integrated coastal planning also intersects with the complex issue of Maritime State Property linked to the concept of competition and competitiveness for the allocation of concessions [6]. This is countered by a wide range of scientific

and administrative sector literature, which contributes to the formation of the "Right to the Sea," understood as the right to freely enjoy the sea and beaches according to the shared approach of "Common Good" [2].

Common goods are described as "shared ownership" resources, implying that they belong to everyone and no one simultaneously. This definition emphasizes that access to these resources should be open to all, avoiding any form of exclusivity. Their management must be based on the principle of solidarity. Since these goods are outside the scope of the market, they serve as an essential tool to ensure the practical application of civil rights, i.e., those rights that every individual has by being a person. However, addressing the topic of common goods as a category distinct from conventional notions of property implies the need for a preliminary investigation into the connection between certain resources and specific rights. Such analysis helps understand how this "collective good" is organized and what internal differences exist.

As Etzioni argues:

The idea of the common good (or public interest) might seem straightforward. It refers to things that benefit everyone and the institutions we value and support together, like national defense or maintaining a clean environment. The common good isn't just a sum of individual benefits; it encompasses aspects that may not directly benefit anyone at the moment, such as protecting national monuments, or that may benefit future generations, like conducting fundamental research. Contributing to the common good might not yield immediate rewards, and it's often uncertain who will benefit from these contributions in the long term. However, we support the common good not necessarily because we expect a direct benefit for ourselves or even our children, but because we see it as something inherently valuable. In simple terms, we do it because it's the right thing, for its own sake—a concept that might only seem surprising to those who believe every action is driven by self-interest [10].

Arena and Iaione describe the Italian context as the opposite of the Italy outlined centuries ago by Guicciardini, which was characterized by a sole focus on personal interest and the belief in the possibility of surviving independently, even at the expense of others. In contrast, there exists a less visible Italy that has been active for years, committed to improving collective life through the management and care of common goods. These include natural resources like water and air, the environment at large, cultural assets, infrastructure, urban spaces, green areas, and extend also to legality and other similar aspects. This approach emphasizes the importance of collaboration and collective responsibility in preserving and enhancing resources that benefit the entire community, reflecting a significant shift towards a more inclusive and sustainable approach in dealing with common goods [1].

Mattei emphasizes their role, highlighting them as integral to a political and cultural approach rooted in collective living. Common goods are seen as a means to reclaim public spaces through a democratic process, prioritizing the quality of human relationships over the accumulation of material goods. This perspective positions common goods not just as physical resources, but also as vehicles to promote a sense of community and to foster richer and more meaningful social interactions, emphasizing the importance of values such as cooperation and sharing in society [16].

Within this synthetic framework is the present research, which aims to represent an integrated approach between environmental protection, enjoyment of the commons between economic competition and national defence, conducted by the same authors within the drafting of the PUL of the Municipality of Villaputzu, Quirra beach (Sardinia, Italy).

2 The Use of Coastal Landscapes in Sardinia

The coastline of Sardinia is about 1,849 km in total length, extending to about 2,400 km, counting the smaller islands. The analysis of the relevant scientific literature, also formalized in the legislation (Regional Landscape Plan-PPR and PUL) of regional reference [14, 19, 23], allows for the classification of three main categories of coastal landscape: natural; historic cities and coastal metropolises; and shores and tourist-bathing conurbations.

Moreover, the coastal landscapes of Sardinia are characterized by significant anthropogenic pressure, accentuated during the summer due to the significant concentration of tourist flows. This is compounded by erosion phenomena, with obvious signs of environmental stress, such as the acceleration of modification of coastal settings and shoreline retreat processes, and reduction/fragmentation of dune habitats, often attributable to inadequate coastal management practices [8]. The Autonomous Region of Sardinia, with the PPR(2006) [21] for the first time made explicit (Art. 43) the regulation of coastal management and the regulation of dunes and sandy shorelines subject to tourist use to ensure the protection of the ecological and landscape structure, accessibility and enjoyment compatible with the widest conservation of natural resources. According to the PPR, the main preparatory actions to ensure the protection and enhancement of the coast [4] consist of the classification of beaches to associate specific objectives with distinct management rules to ensure minimum services, such as accessibility and rest, points for refreshment, sports and leisure, etc., provided by private parties following state concession for the possible installation of temporary architecture consistent with the landscape. The Autonomous Region of Sardinia has therefore recognized in the PUL the main implementation tool through which municipalities, within the framework of the delegations to the Municipalities of Sardinia under Article 41 of Regional Law 9/2006 (Transfer of functions and tasks to local authorities), can plan within the Maritime State Property for tourism and recreation purposes.

3 Coastal Use Plan in the Island Context of Sardinia

Regional Law 9/2006 gave Sardinia's municipalities the task of managing and approving PULs, and granting permits for tourist-recreational activities in Maritime State Property or inland navigation areas, provided these activities are carried out in open areas or with easily removable structures. This law also assigns other administrative responsibilities related to the maritime state property and the territorial sea to municipalities that the region or the state does not exclusively manage. The PULs are also intended to organize the areas close to the coastline, including road and pedestrian access and the use of places of interest, consistent with Article 29 of Regional Law 23/1985 and its subsequent amendments and additions.

The guidelines contained in the "Guidelines for the drafting of the PUL and the exercise of administrative functions in the field of Maritime State Property and areas of the territorial sea" appear to be aimed at:

1. ensure the conservation and protection of local coastal ecosystems, with particular reference to areas protected by Presidential Decree 357/1997 (implementing Directive 92/43/EEC on the conservation of natural and semi-natural habitats and of wild flora and fauna) and individual marine protected areas;
2. harmonize actions on the territory for sustainable development, in particular by encouraging measures to reduce the processes of degradation and indiscriminate land consumption;
3. promote and encourage environmental redevelopment through projects for the renaturalization of bathing establishments, with the replacement of fixed structures with structures in precarious, and in any case with low environmental impact, and their removal from the shoreline;
4. ensuring continuity between the shoreline, dune cordon and ecological corridor by improving the accessibility of state-owned maritime areas;
5. encourage innovation and diversification of tourism offerings;
6. regulate the different activities for integration and complementarity between them;
7. constitute a framework aimed at harmonizing the actions of public and private entities on the coastal strip.

The case study of the PUL of the Municipality of Villaputzu (Sardinia) fits into this concise framework.

4 Material and Method

4.1 The PUL of the Municipality of Villaputzu. Quirra Beach as a Case Study

The municipal territory of Villaputzu is located in the Province of South Sardinia, in the historical subregion of Sarrabus, located in the southern eastern coastal slope of Sardinia (Fig. 1). It occupies an area of about 181 km^2 with a resident population of 4,509 [11].

A linear development of 24 km characterizes the coastal portion of the territory. The Maritime State Property insisting in the Municipality of Villaputzu extends from Cape Sferracavallo to the south of the Flumendosa mouth, at Flumini Mannu. The urban settlement of Villaputzu, is articulated of three portions: the urban center characterized mainly by the historic core and expansions before the 1960s, the settlement of Santa Maria and the recent coastal tourist settlement of Porto Corallo with its namesake and nearby marina.

In this multipolar urban layout, the PUL of the Municipality of Villaputzu fits into six areas: beach de Is Santuidedus; Foce del Flumendosa; First beach-Prumari; Porto Corallino Beach; Porto Tramatzu beach; and Murtas or Quirra beach (Fig. 2).

The presence of the vast military area (about 120 km^2), which occupies about one third of the entire territory in the Municipality of Villaputzu, required an innovative approach, especially in the beach of Quirra, to reconcile protection and conservation needs with military uses (exercises) and civilian uses (recreational bathing).

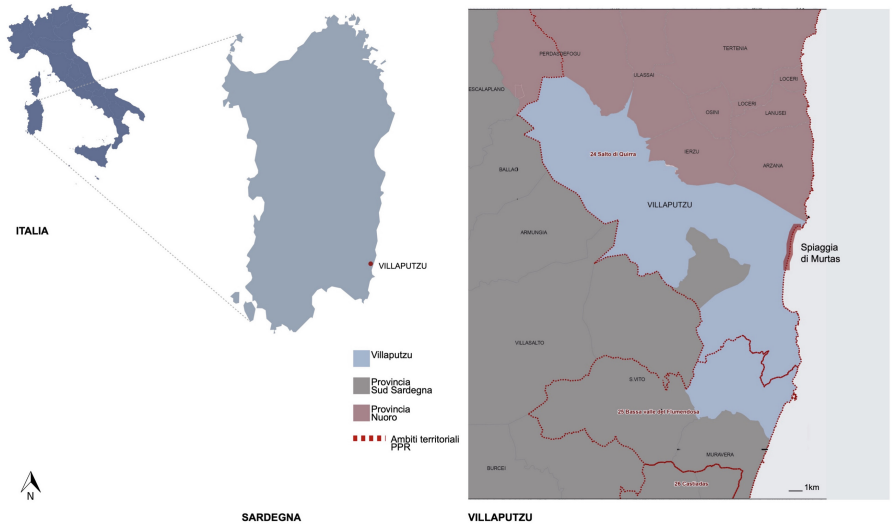


Fig. 1. Spatial setting.

Quirra Beach, the subject of this case study, is located in the Capo San Lorenzo stretch of coastline. From the Directory of Sandy Coasts of Sardinia, annexed to the PPR, it can be seen that the sandy compendium of Quirra beach has a length of about 12,914 m and an area of about 29.3 hectares and is all under military constraint. This beach can only be reached by land, for vehicle parking there are a total of 250 parking spaces.

For decades, access to Quirra beach has been barred due to the insistence of the Interforce Experimental Military Polygon of Salto di Quirra.

However, in 2017, a special agreement was reached between the municipality of Villaputzu and the unique military polygon that allows the beach to be open to the public during the summer (June to September) without military exercises. Only a portion is still interclosed due to stricter military restrictions.

In addition, Quirra beach is included in a Site of Community Interest - SCI (Stagni di Murtas e s'Acqua).

In this concise framework, the methodology proposed in the Quirra beach PUL aims to promote the transition "*from Anti-commons to Semi-commons*" through an integrated approach between environmental protection, military constraints and competitive private economic development under the Bolkestein Directive 2006/123/EC through temporary state concessions. More generally, Villaputzu's PUL outlines a model of sustainable beach management and enjoyment, regulating uses and defining their spatial distribution in detail (Fig. 3).

As result of the subsistence of two conflicting regulatory apparatuses, namely the one related to the military and environmental polygon of the SCI required how the elaboration of the PUL was supported by both the Environmental Impact Assessment and the Strategic Environmental Assessment, allowing for the identification of mitigation actions, such as contingent use. Moreover, the contextual persistence of competing interests [28]

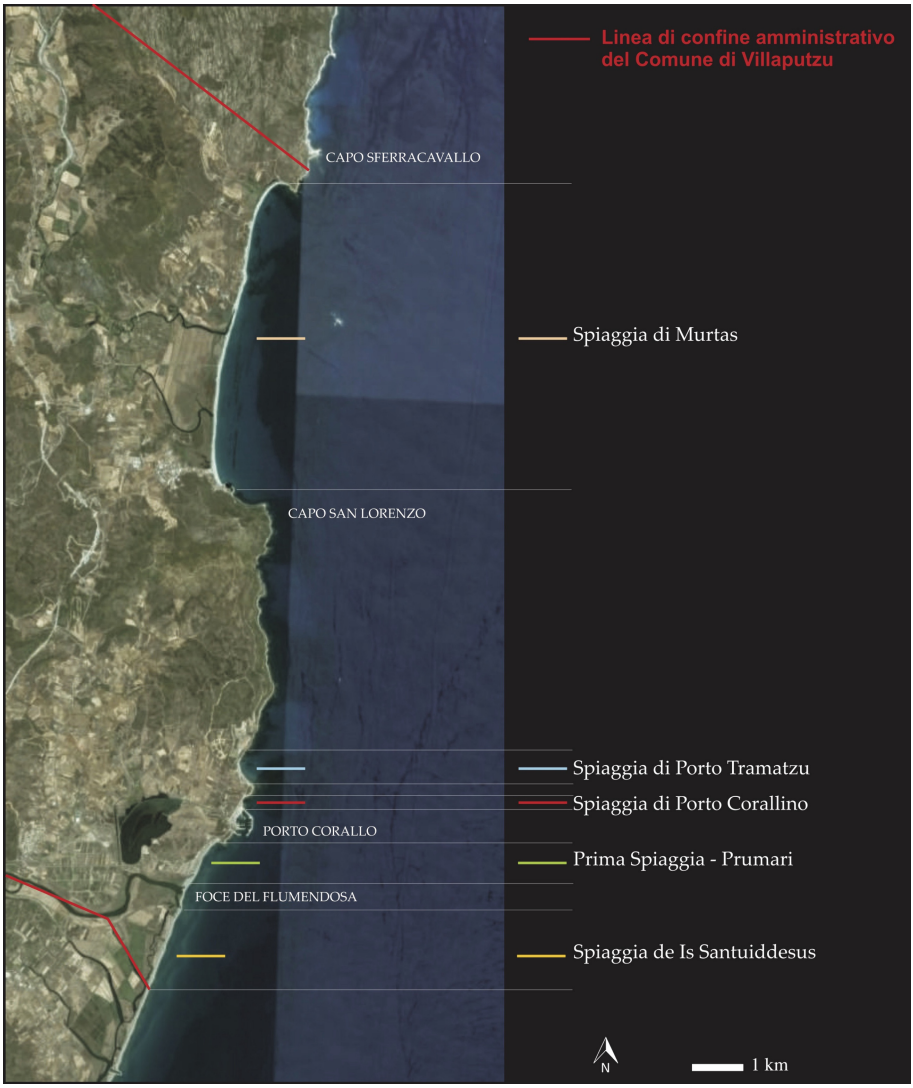


Fig. 2. Beaches of the Municipality of Villaputzu Source: PUL of the Municipality of Villaputzu.

required participatory planning with the local community, achieving greater awareness of the coastal environmental resource's gradual transition of use, from military to civilian [1, 2].

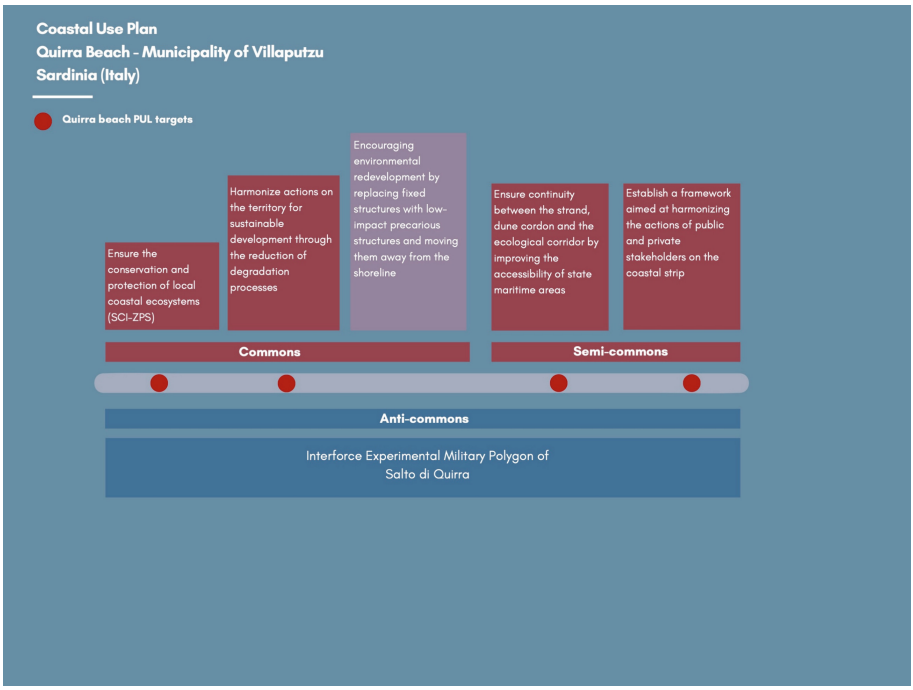


Fig. 3. Objectives of the Quirra Beach PUL. (from Anticommons to Semicommos - Commons)

5 Discussion and Conclusions

The specificity of the coastal zone as a sensitive area, as an irreproducible and increasingly reduced resource directs coastal planning and management towards models of land management and land use capable on the one hand protecting the environmental heritage, and on the other hand allowing a conscious use of the territory. Development in these directions does not coincide with physical growth, even more so in the coastal territory, so the guiding principle of coastal planning, which directs the transformation of the territory supported by adequate measures to control growth and direct development, is affirmed.

A strong seasonal tourism pressure persists in the coastal landscape of Sardinia [7], although radical changes in digital innovation in favor of sustainable tourism have occurred, the PUCs are still strongly rooted in the static approach of zoning and have little impact on the important problems arising from the spatial distribution of seaside tourism [27].

The PUL represents the operational tool for a renewed vision and strategic planning capable of fully implementing the Bolkestein Directive 2006/123/EC, which in the case of the case of Quirra provides for the allocation of beach concessions by public tender, able to ensure environmental protection and socio-economic enhancement through public-private partnership (art. 174, paragraph 1, of Legislative Decree no. 36/2023).

Adopting sustainable development policies, preserving the natural and cultural environment and promoting cultural and socio-economic initiatives contribute to preserving the identity and well-being of communities [5].

The transition of Quirra beach from military to civilian (temporary) use, i.e., from "Anticommons" to "Semicommons or Commons," represents a case of significant relevance in the Italian scenario. In particular, the configuration as "Semicommons" incorporated the private tourism and beach services sector; the "Commons" configuration is based on environmental protection in line with the Management Plan of the Sic of Villaputzu, which limits the overuse of the coastline by contingenting the use.

The case of Quirra beach was a precursor of a gradual demilitarization process recently initiated (December 2023), which involves other stretches of coastline in Sardinia. In this sense, the PUL guides the aforementioned transition, proposing a tourism scenario compatible between the conservation and enhancement of the natural heritage and superordinate national-level interests (military defense), through careful monitoring proper to integrated planning [9].

Funding. This research received no external funding.

References

1. Arena, G., Iaione, C.: L'Italia dei beni comuni. Carocci (2012)
2. Balletto, G., et al.: Military training areas as semicommons: the territorial valorization of Quirra (Sardinia) from easements to ecosystem services. Sustainability **12**(2), 622 (2020). https://doi.org/10.3390/su12020622
3. Battino, S., et al.: Smart and slow tourism in protected natural context. In: Computational Science and Its Applications – ICCSA 2023 Workshops: Athens, Greece, July 3–6, 2023, Proceedings, Part VIII. pp. 64–74 Springer-Verlag, Berlin, Heidelberg (2023). https://doi.org/10.1007/978-3-031-37126-4_5
4. Cadeddu, B., et al.: Dismissioni militari e valorizzazione del patrimonio costiero. Il caso della AgenziaConservatoria delle coste della Sardegna. Urbanistica Dossier (2022)
5. Cardillo, M.C., et al.: Isole, turismo e ambiente: tra conflitti, modelli e opportunità. Geotema 67 (2021)
6. Carlin, M.: Concessioni demaniali marittime e lacuali. Problemi e casi pratici. Key Editore, Milano (2019)
7. Cazzari, C., et al.: Evoluzione del costruito nelle aree costiere della Sardegna. Fra sviluppo economico e vulnerabilità ecologica. ARCHIVIO DI STUDI URBANI E REGIONALI. 2022/134 (2022). https://doi.org/10.3280/ASUR2022-134002.
8. De Muro, S., et al.: EVOLUZIONE RECENTE, REGIME, ASSETTI, CRITICITÀ, TENDENZA DEL SISTEMA SPIAGGIA DI CALA CIACCARO. Presented at the January 1 (2012)
9. Floris, M., et al.: Valutazione ambientale strategica, piani urbanistici comunali e piani dei parchi. (2022). https://doi.org/10.13125/unicapress.978-88-3312-103-1
10. Lo, P., Solomon, D.: The Common Good. In: David Solomon, P.C., Lo, (eds.) The Common Good: Chinese and American Perspectives. PSCC, vol. 23, pp. 3–18. Springer, Dordrecht (2014). https://doi.org/10.1007/978-94-007-7272-4_1
11. ISTAT: Istat.it. https://www.istat.it/. Accessed 27 Dec 2023
12. ISTAT: Rapporto sdgs 2020. Informazioni statistiche per l'agenda 2030 in Italia. (2020)

13. Leone, F., Zoppi, C.: Misure di conservazione dei Piani di gestione dei Siti Natura 2000 e Piani di utilizzo dei litorali a confronto. Uno studio riguardante l'Area del Sulcis, Sardegna. In: Atti della XXII Conferenza Nazionale SIU, L'urbanistica italiana di fronte all'Agenda 2030. Portare territori e comunità sulla strada della sostenibilità e resilienza. Matera-Bari, pp. 5–6–7 giugno 2019, Planum Publisher, Roma-Milano (2020)
14. Loi, A.: Sardegna. Geografia di una società. AV (2006)
15. MASE: Gestione Integrata Zone Costiere (GIZC) | Ministero dell'Ambiente e della Sicurezza Energetica. https://www.mase.gov.it/pagina/gestione-integrata-zone-costiere-gizc. Accessed 27 Dec 2023
16. Mattei, U.: Beni comuni. Un manifesto. Laterza (2012)
17. Ministero della salute: Rapporto acque di balneazione (2010). https://www.salute.gov.it/imgs/C_17_pubblicazioni_1291_allegato.pdf
18. Montebello, C.: La gestione integrata e sostenibile delle zone costiere nel diritto internazionale. Rivista di diritto dell'economia, dei trasporti e dell'ambiente (2004)
19. Mori, A.: Sardegna. Unione tipografico-editrice torinese (1975)
20. Parlamento Europeo: RACCOMANDAZIONE DEL PARLAMENTO EUROPEO E DEL CONSIGLIO del 30 maggio 2002 relativa all'attuazione della gestione integrata delle zone costiere in Europa (2002). https://www.mase.gov.it/sites/default/files/archivio/normativa/celex_32002h0413_it_raccomandazione.pdf
21. RAS: Piano Paesaggistico Regionale (2006). https://www.regione.sardegna.it/documenti/1_274_20131030211420.pdf
22. Ruol, P., et al.: Gestione integrata della zona costiera. Studio e monitoraggio per la definizione degli interventi di difesa dei litorali dall'erosione nella Regione Veneto-Linee guida. Edizioni Progetto Padova, Padova (2016)
23. Tanca, M.: Paesaggio-tutela o paesaggio-vincolo? 15 anni di pianificazione paesaggistica in Sardegna (2004–2019). Ri-Vista. 24–39 (2019). https://doi.org/10.13128/RV-8312
24. UN: Agenda 21 - Chapter 17. In: report of the united nations conference on environment and development. United Nations (1992)
25. UN: UNCLOS and Agreement on Part XI - Preamble and frame index (1982). https://www.un.org/Depts/los/convention_agreements/texts/unclos/closindx.htm
26. UNRIC: Obiettivo 14: conservare e utilizzare in modo durevole gli oceani, i mari e le risorse marine per uno sviluppo sostenibile. https://unric.org/it/obiettivo-14-conservare-e-utilizzare-in-modo-durevole-gli-oceani-i-mari-e-le-risorse-marine-per-uno-sviluppo-sostenibile/. Accessed 29 Dec 2023
27. UNWTO: Tourism Statistics Database. https://www.unwto.org/tourism-statistics/tourism-statistics-database. Accessed 28 Dec 2023
28. Vitulli, L.: La regolazione delle zone costiere: le concessioni demaniali marittime fra concorrenza e tutela ambientale. Rivista Quadrimestrale Di Diritto Dell'ambiente. 341–381 (2022)

Post-seismic Reconstruction Planning. A Space-Time Scheduling Multi-prospects Model

Maria Rosa Trovato[1(✉)], Ludovica Nasca[1], Vittoria Ventura[1], Salvatore Giuffrida[1], and Filippo Gagliano[2]

[1] University of Catania – DICAr, Catania, Via S. Sofia, 64, 95123 Catania, Italy
mrtrovato@dica.unict.it, ludovica.nasca@phd.unict.it, salvatore.giuffrida@unict.it
[2] Department of Geomatics – ITS G. Quarenghi, Bergamo, Italy

Abstract. The post-earthquake reconstruction of the small-town centers included in the "seismic crater" of Abruzzo (Italy) in 2009, affected by one of the most serious natural disaster in the recent Italian history, was managed through various phases, involving the typical cognitive, evaluative and decision-making functions of appraisal and valuation. This paper presents the latter, which deals with the planning of the reconstruction works, a decision-making process that involves the whole cognitive spectrum of the ontology, epistemology and praxeology of the human, urban and social capital. With reference to the case study of a small-town center, the proposed space-time multi-prospect model is structured in two different approaches: the first, static, takes into account the attributes as defined upstream; the second, dynamic, takes into account the changing conditions that occur year after year as the reconstruction progresses, changing the topography of the attractors. In the planning phase, the value of the spatial characteristics of the individual units targeted for funding was identified and characterised; in the concertation phase, the building aggregates worthy of intervention were identified and mapped; in the decision phase, the preference system was redefined by creating multiple scenarios with a view to the final optimisation of the public funding programme.

Keywords: Value-based planning · Disaster proactive vs reactive policies · Scenarios generation

1 Introduction

1.1 Framework

This paper frames within the whole spectrum of the Appraisal and Valuation discipline, implying a specific civic engagement in the reform of the home-city-landscape system [1]. This implication concerns the original reference of value and valuation science (once Appraisal) to issues of distributive justice.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 141–158, 2024.
https://doi.org/10.1007/978-3-031-65238-7_10

Among the many operational areas of distributive justice – in particular spatial – the balance between proactive and reactive approaches in territorial risk prevention policies [2–4] includes all the most important and urgent aspects of the dialectic between citizen and *res publica*: the relationship between individual and community, state and market, home and city, city and territory, wealth and value, converging towards the land-economic general category of human-urban capital [5].

The Italian legal system guarantees reconstruction with public funds in the event of an earthquake, while leaving prevention choices and decisions to local authorities and households. For this reason, the insurance sector in Italy has a weak presence in the field of protection against natural disasters and, in particular, against earthquake risk [6].

Recently, as part of the post pandemic "National Recovery and Resilience Plan" (NRRP) [7], the Italian government has guaranteed a substantial set of measures to support quality costruction, in particular seismic and energy retrofitting, but nevertheless on a voluntary basis and therefore without coordination at the urban or neighbourhood level. As a result, there is still a high level of vulnerability at the territorial level of the built heritage exposed to seismic risk.

This paper presents a study case of reactive policy, in particular a value-based multi-prospects programming model for the post-seismic reconstruction process over experienced in one of the small-town centres [8] included in the wide seismic crater as a consequence of the Abruzzo earthquake of 6 April 2009.

This disaster dictated the establishment of a massive administrative machinery to oversee all the phases of reconstruction, from the typically cognitive ones, i.e. the identification of information units (building aggregates and building units) evaluation, damage classes and parametric reconstruction costs, to the decision-making ones, such as the drawing up the reconstruction timetable, all with the aim of ensuring that public fund do not exceed what is due, thus guaranteeing the balance between the (dis-)value of the damage and the value of the public resources allocated to its compensation.

This correspondence between the value of the damage and the value of the public funding (the latter to be taken as the social opportunity cost) is to be related to the original principle of welfare economics, which implies the internalization of the externalities, which we interpret and propose as a prospect of solidarity based on the value of merit.

Accordingly, the governance of reconstruction has always been aimed at ensuring a fair distribution of funds based on a rigorous assessment of the funding merits of reconstruction works.

1.2 Contents and Aims

Based on the two main contents of the reconstruction plans – the valuation of the reconstruction costs and the timetable – the paper aims to provide a model for the space-time allocation of public funds for the Reconstruction Plan of the Municipality of Fossa (Italy) (Fig. 1), one of the most relevant small-town centres of the seismic crater from the urban, architectural, historic, anthropological and landscape point of view.

The paper presents the main conceptual issues of the creation of the model across the three main cognitive functions, analysis, evaluation and project, and some of its possible applications. Analysis aims at setting the information system at the two levels of Building Units (BUs) and Building Aggregates (BAs). Valuation defines the four axiological

perspectives, the value functions and the weighting systems related to different socio-economic prospects, and sets up the static and dynamic approaches. The project includes the programming functions, which outline multiple scenarios each related to a different socio-economic perspective.

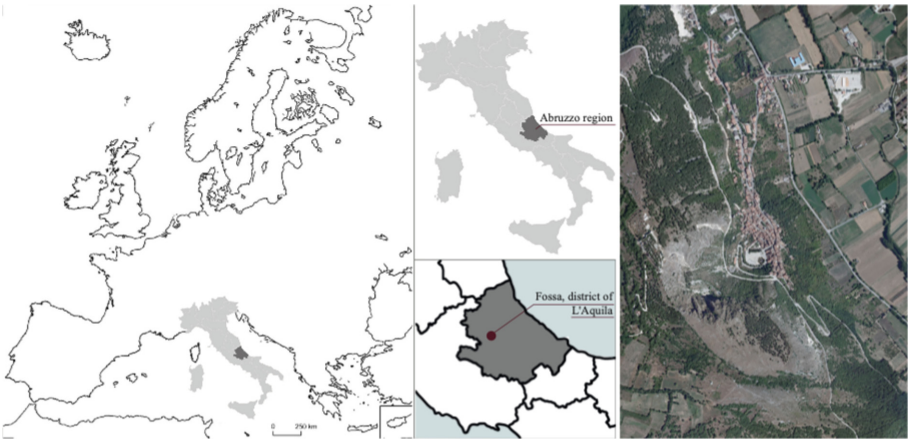


Fig. 1. Geographical outline and orthophoto of Fossa small-town centre.

The paper is divided into five parts. Section 2 (Materials) summarizes the territorial and administrative background ruling the Reconstruction Plans drafting and a short description of the study case. Section 3 (Methods) presents the multi-perspective space-time scheduling model for the equitable allocation of the reconstruction fund. Section 4 (Application) presents and describes the results of the experiment according to the different scenario hypotheses. Section 5 (Discussions and conclusions) presents some critical considerations about the many epistemological and axiological oppositions that characterize the many issues of the community security management.

2 Materials

The Abruzzo earthquake of 6 April 2009 affected an area, the seismic crater, of 2387 km^2, comprising 56 municipalities and the regional capital, L'Aquila, involving 67,000 inhabitants, who were initially housed in temporary accommodation and hotels, and then in two types of residential complexes, the Provisional Housing Modules (PHM) and the Sustainable and Environmentallly Friendly Earthquak Resistant Complexes (SEEC). Due to the enormous economic commitment required for their construction, they have become a medium to long-term locational prospect, such as new territorial poles that have changed the planning of the territorial structure.

The financing of reconstruction involves an imposing administrative machinery, which is called upon to coordinate all levels of the process in order to implement the progressive and joint legislative action of the national and regional governments, represented by the Prime Minister and the Deputy Commissioner for Reconstruction, the President of the Region.

The various Ordinances of the Italian Prime Minister (OPM) have regulated the eligibility for compensation (classification of the state of damage on the basis of usability) also based on the rights for first and second homes (OPM 3779/2009), actions directly or indirectly related to earthquake damage, reconstruction works and socio-economic development, also specifying the limits of the exceptions to the principle of compensation in a specific form (transfer of buildings and relocation), the conditions and contribution limits for the less severe (A) individual and aggregate (OPM 3820/2009) and more severe (E) classes of usability (OPM 3778, 3779 and 3790/2009 and 3881/2010), the increase in the parametric costs for buildings of architectural value and listed buildings (OPM 3917/2010) etc., with the general intention of protecting and qualifying public expenditure.

Implicitly, the Technical Mission Structure was intended to limit the excesses of that "disaster economy" which, in an exceptional situation is inevitably triggered by the convergence of the contingent emergency and the prospective huge flow of money which the various professions, companies, and local administrations rush to capture for purposes linked to both personal interest and to collective value, not always convergent and harmonious.

The Decrees of the Delegate Commissioner for Reconstruction [9] have regulated the path of eligibility for funding:

- by introducing the Reconstruction Plans (Decree-Law 39/2009), which aim to implement the contextuality and processuality of reconstruction;
- by indicating the modalities of the perimeter (Decree-Law 3/2010);
- by distinguishing homogeneous areas and buildings to be recognised as recipients of systematic and integrated works, coordinated by Consortia.

The very intention was to adapt the principle of individual compensation to the legal-administrative realities resulting from the combination of settlement characteristics and construction aspects; consequently, the delimited areas are divided into areas within which the building aggregates to be supported are identified.

From the outset, the government, which was very concerned about the fairness of compensation, the efficiency of public spending and the transparency of the procedures, focused on programming in the crater area with the publication of the State of Implementation and Programming, which allocated to each of the 20 municipalities, out of a total of 56 that had adopted the Reconstruction Plans (RPs) at that time, a variable share of the funds indicated in the corresponding Technical and Economic Frameworks (TEFs). The priorities depended on the number of main dwellings and aggregates including main dwellings, and on the number of social housing units and monuments.

Now, while the drafting of the TEF was defined by the regional technical bodies in such a way as to allow the funds to be distributed among the municipalities according to their real needs, the drafting of the Timetable was not complemented by rules for measuring and comparing the values of social, urban, cultural and economic capital in order to be able to define preferences and priorities [10] among the different shapes of salience and urgence.

This contribution aims to bridge the gap between shared awareness and top-down decisions in the formation of a Timetable for post-earthquake reconstruction, based on

the integration of saliencies and urgencies through a value-based programming model developed within a Web-GIS modelling environment.

3 Method

3.1 Approach and Axiological Coordinates

The Timetable is a planning document that defines the space-time allocation of funds between the different eligible parties: Consortia (BAs), condominiums (BUs including different properties), homeowners (mono-property buildings) (BAs in the three cases).

A MAVT-based approach allows the ranking of the BAs according to their attitude toward financing; the generation of multiple scenarios and their evaluation on the basis of four axiological matrices allows the maximisation a multi-prospect function.

Making criteria and their comparative importance explicit makes it possible to compare different strategies for supporting participatory decision-making. This dialogical support makes it possible to limit discretion by specifying the fraction of it that cannot be axotomized, in particuar with regard to the following elements:

- *steps*, i.e. the stages of the decision-making process in which discretion is concentrated, including the choice of criteria, the weighting system and the value functions; in particular, in order to satisfy certain explicit requests from the administration, the model allows each of the criteria to be assigned a dominant position and the related value functions a specific score range depending on whether that criterion is dominant (i.e. it must be satisfied first) or semi-dominant (i.e. whether the BAs that best meet this criterion are favoured to a certain extent) [11];
- *breadth* of the sphere of actors exercising this discretion, and thus of the sphere of interlocution; the value-based participatory model [12] is supported by a WebGIS interface [13] that allows accredited actors to implement the parameters that correspond to their specific axiological profile and to visualise the corresponding spatio-temporal funding plans in real time;
- *destination*, i.e. the subjects and objects on which discretion has the greatest effect; given the vagueness of the rules and procedures, these effects concern the local responsibility and the search of consensus, rather than the possibility of affirming shared values in the wider context of the crater.

The approach is based on two distinct and converging cognitive functions: 1. The evaluation (static and dynamic) of BAs; 2. The programming of reconstruction interventions. These two levels of evaluation refer to general criteria of fairness, effectiveness, economy and efficiency.

- *Fairness.* This is the socio-economic criterion that refers to the primary objective of reconstruction, which is the return of primary dwellings to displaced persons housed in temporary shelters. This criterion priotitizes: 1. The Bas with a higher percentage volume of primary dwellings; 2. The strategies that envisage a shorter time for the completion of the reconstruction of primary dwellings.
- *Effectiveness.* This criterion concerns the possibility of reactivating strategic (central) urban contexts first; it gives priority to: 1. The BAs closest to the areas with the highest

density of functional and symbolic value; 2. The average completion time of central building reconstruction.
– *Cost-effectiveness.* The built-urban heritage is characterised by different attributes of real estate value [14]; the first two criteria cannot take this into account, nor can the principles of compensation go out of their way to privilege a predominantly private patrimonial dimension: 1. Preference will be given to BAs characterised by the features usually most valued by the real estate market; 2. The strategy that concentrates in the first years the buildings that express the greatest share of this value overall will be valued.
– *Efficiency.* As a ratio of outcome to cost, preference will be given to: 1. The least damaged BAs; 2. Strategies that will concentrate the reconstruction of the least costly AEs in the early years.

3.2 The Model. Valuation and Decision-Making Pathways

The cognitive and operational path leading to the best organisation of the Reconstruction Plan [15] is a decision-making process in which Analysis, Evaluation and Project overlap and merge. Figure 2 shows the three cognitive functions and domains, marked with different colours.

Analysis: provides a discrete representation of the urban fabric, first through Building Units that are identified and characterized according to a standard lexicon associated to Building Urban, Economic and Social value attributes.

Evaluation:

– on a building scale ("House matters!"), a preference system [16] stemming from a predominantly individual axiology, transforms observations into valuations that define Saliences and Urgencies; this transformation allows the attributes of the BUs to be projected onto the BA scale; the BA is now the minimum information/value-bearer unit, as well as the urban elementary unit whose Aptitude to be financed is defined in terms of Weighted Average Scores (WAS) using the MAVT-based decision-making model;
– on an urban scale ("Citizenship matters!") the Community's ethical prospects project the BAs Aptitudes towards the dimensions of Space (Saliences) and Time (Urgencies).

Project:

– in the Space dimension at the level of the BAs Aptitudes the programming functions generate a set of Strategies (reconstruction layouts) each of which represents a different preference system defined by a different weighting system: fairness-effectiveness/efficiency-cost-effectiveness;
– in the Time dimension the model adapts itself by changing some of the rules of the valuation model from year to year, making decisions dynamic.

As summarised above, the model consists of:

1. two evaluation paths which aim to outline as many rankings of BAs as there are strategies to be implemented. These rankings can be established according to:

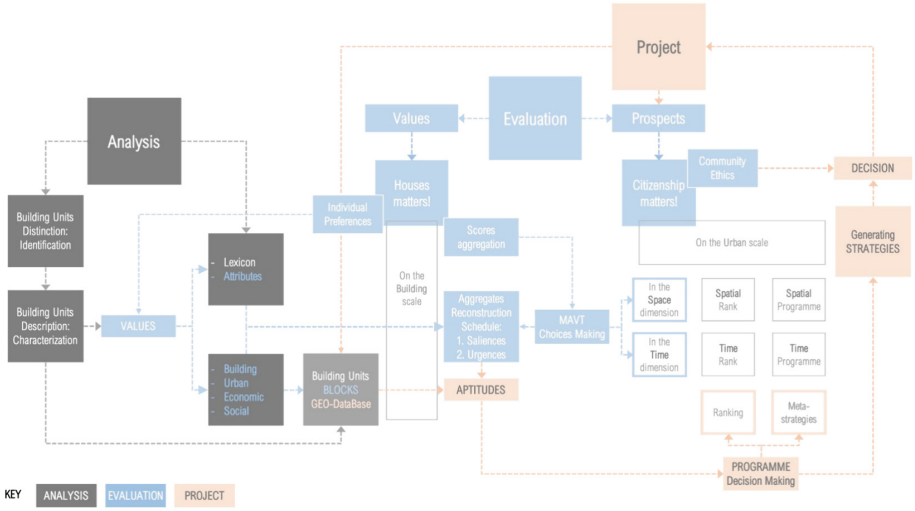


Fig. 2. Conceptual map of the cognitive-operational pathway of the reconstruction Timetable.

a. a static evaluation path;
b. a dynamic evaluation path;

2. two programming levels:
   a. the choices level, which is aimed at the BAs and therefore at their ranking in relation to the two paths and each strategy;
   b. the decision level, aimed at the strategies, developing on a meta-strategic level.

3.3 Valuation Pathway. Static and Dynamic Assessments

The aim of these assessments is to characterise BAs in order to determine their eligibility for funding.

Static Valuation. It assumes that axiological semantics – I.E. The rules by which the preference attribute is associated with the value-bearer – are invariant throughout the reconstruction process. The problem of the best allocation of the annual reconstruction budget is approached by maximising a multi-attribute function [17]. The BAs that rank highest in terms of funding merit are selected until the budget is exhausted; the remainder is added to the following year's budget.

The ranking position of the i_{th} BA depends on the score $S_i = \overrightarrow{s_{hi}}\,\overrightarrow{\lambda}$, where $\overrightarrow{s_{hi}}$ is the vector of the $h = 1, 2, \ldots 4$ scores assigned to the BA from the perspective of each attribute, while $\overrightarrow{\lambda}$ is the vector of weights assigned to the attributes with the constraint that $\sum \lambda = 1$.

Since each BA is made up of m BUs with each of which is associated with a vector of four scores $\overrightarrow{u_{ki}}$, $(k = 1, 2, \ldots m)$, varying on a dimensionless scale between 0 and 2, the single s_{hi} is calculated by aggregating all the u_{hk} of the m BUs included in the BA. There are $j(1, 2, \ldots, 4)$ different ways of aggregating the m u_{hi} of the i_{th} BA:

- $s_{hi1} = \sum_k u_{hk} v_{ki} / V_i$, where v_{ki} is the volume of the k_{th} BU and V_i is the total volume of the i_{th} BA;
- $s_{hi2} = \sum_k u_{hk} \overline{V}_k$, where $\overline{V}_k = v_{ki} / \sum_i V_i$;
- $s_{hi3} = u_{hk} / m$;
- $s_{hi4} = \sum_k s_{hk} g_{ki} / G_i$, where g_{ki} is the ground area of the k_{th} BU of the i_{th} BA, and G_i is the total ground area of the BA.

The total score for each of the 72 BAs is: $\forall BA_i \in BA, \exists f_1(BA_i) = S_i; 1 \leq BA_i \leq 72; 0 \leq S_i \leq 2; f_1$ normalizes the average weighted *scores* to a 0–2 standard scale.

The reconstruction cost C_i for each BA is obtained from the TEF: $\forall BA_i \in BA, \exists f_2(A_i) = C_i; f_2$ implements the OPMs conditions [18] to calculate C_i [19].

Each weighting system generates a different ordering of the BAs, and for each annual budget W_y, $(y = 1, 2, \ldots, 6)$, a subset $D \subset AE$ is defined, where D contains the top BAs whose total cost do not exceed W_i. Correspondingly:

$$\forall W_i \exists D \subset AE : \sum_{i=1}^{m} C_i \leq W_i$$

A synopsis of the above model with reference to the BUs and BAs assessments is shown in Fig. 3.

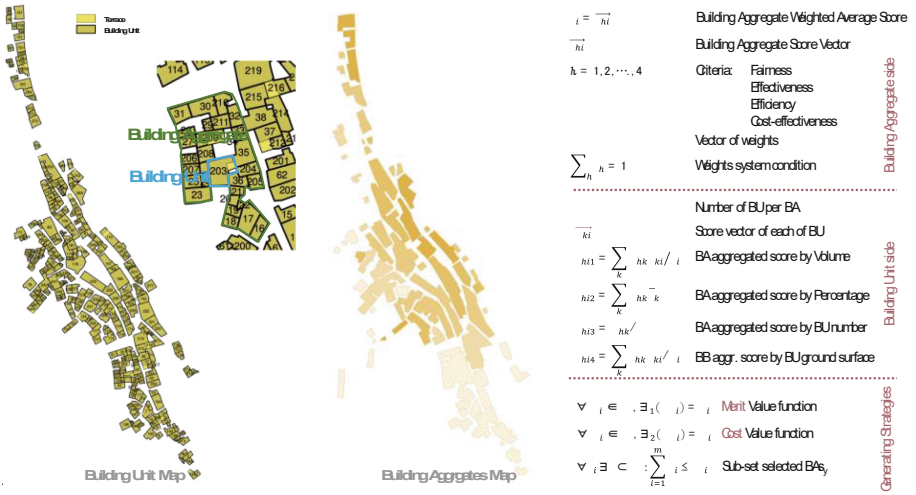


Fig. 3. Synopsis of the evaluation model for the ranking of the BAs by eligibility for funding.

Dynamic Valuation. It admits that the axiological semantics may change from year to year as reconstruction continues. This idea stems from the perception of how the wounds inflicted by the earthquake and the emergency garrisons have merged together, are established themselves as new presences that, for better or for worse, will accompany the future of these territories with new histories and new geographies. As a result of this bifurcation, reconstruction is no longer restoration, but progressive adaptation that

deviates from the natural course of events. The dialectic of principles (the values) and contingencies (changes in conditions) is the subject of the project evaluation a double awareness that enables decision-makers to act on the basis of reason and truth.

The dynamic modelling took into account the change in location attributes as the reconstruction progressed from year to year. Figure 4 shows, in a hypothetical abstract space, two rows of four rectangles whose cells symbolize the BAs in terms of Attributes and Aptitudes.

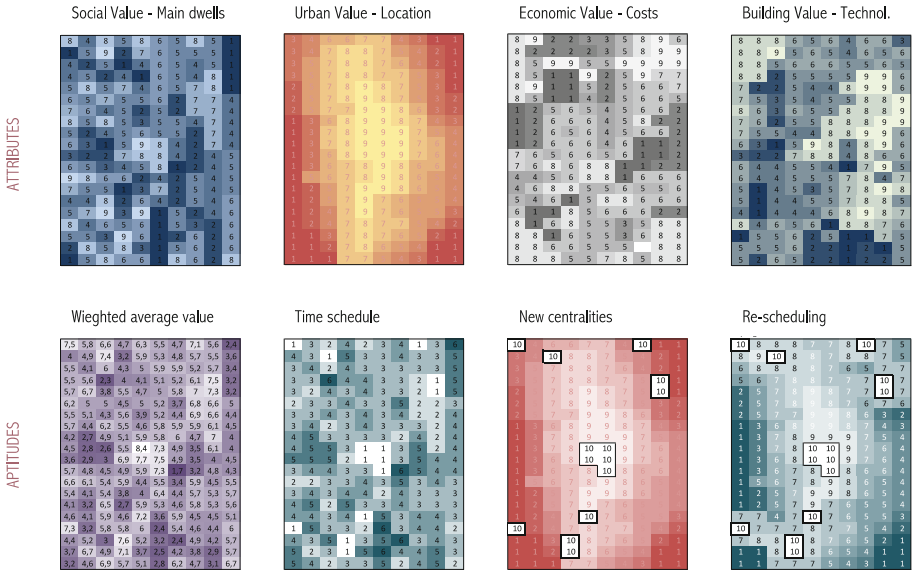


Fig. 4. Dynamic pattern for strategy oulining.

The “Attributes” rectangles – in the above line – are scored from 1, dark, to 10, light, and relate to the four criteria. In particular, the second one, “Urban Value – Location” highlights in yellow a hypothetical more valuable area, formed by a longitudinal road axis and a square in the centre. The other three, mapping Social, Economic and Building values, display the hypothetical random distribution of these values.

The “Aptitudes” rectangles – in the bottom row – display:

- the overall weighted average score;
- the timing of the intervention during the funding period (lighter green for the first years, darker for the last);
- the New centralities generated by the first-year reconstructions in relation to the scheme referable to the Urban value criterion;
- modification of the centrality attribute of all other BAs (light haloes around the BAs reconstructed in the first year) according to the reciprocal distances between them.

In the dynamic pattern, the ranking changes from year to year according to the valorization of the urban context, due to the progressive reconstruction of the BAs,

which in turn create "new centralities", thus influencing the Urban value of the closest ones. Due to the fact that the BAs that are gradually being rebuilt become attractors for the next ones, which may change places from the previous ranking: ${}^{a}S_i = \overrightarrow{s_{h'i}}\,\overrightarrow{\lambda'}$; $(a = 1, 2, \ldots, 6)$ where $\overrightarrow{s_{h'i}}$ is the new vector including the score related to the new criterion "New centralities" and $\overrightarrow{\lambda'}$ is the new weights vector; the first year score is ${}^{1}S_i = S_i$. The greater the weight associated to the new criterion the more significantly the new ranking will differ from the base ranking.

Two different types of dynamic strategy have been implemented: the first assumes that the weight of the new criterion is kept constant; the second outlines four strategies each representing a different situation of a function outlining the trade-off between the basic criteria and the new ones.

3.4 Decision-Making Pathways. The Two Levels of Programming

Programming involves two levels of decision-making:

- the first one involves the generation of internally consistent layouts, i.e. addressing the generation of strategies according to a different weighting system;
- the second one concerns the selection of the best strategy according to the second level of criteria.

Figure 5 shows the weighting systems that generate the 24 strategies: 1–6 cluster concerns the Static approach emphasising the trade-off between qualitative and quantitative criteria; the 7–15 cluster concerns the Dynamic approach 1, emphasising the same trade-off between criteria; the 16–24 cluster concerns the Dynamic approach 2 emphasising the trade-off between the static and the dynamic criteria.

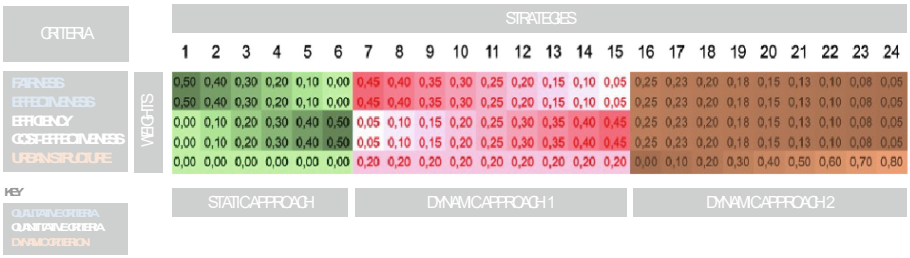


Fig. 5. Scenario generation by combining static/dynamic approaches/criteria and the associated scores by the perspectives of the different criteria.

3.5 The Timetable Web-GIS Platform

The GIS platform of the Fossa RP, in addition to containing all the information of the plan, was used to:

- the implementation on a geodatabase of data from different networked workstations operating on the same database at the same time and without conflicts;

– automate spatial calculations and eliminate errors;
– the link between the contents of the RP and the TEF;
– the spatial analysis necessary for the scoring of the different BAs;
– the dynamic formation of the sorting of the BAs on the basis of evaluations whose functions have been implemented on the same WebGIS platform.

The WebGIS interface consists of several areas (Fig. 6):

– the map and its dynamic zoom functions to adapt the dimensions of the different graphical objects to the different scale ratios; each object can be queried for its characteristics and different themes can be displayed simultaneously;
– an information area on the right-hand side where the required thematisms can be displayed on a map;
– a planning area on the left where the weights of the four criteria are entered, the way in which the AU scores are aggregated (from 1 to 4), the budget for each year, and the possible degree of dominance of each criterion.

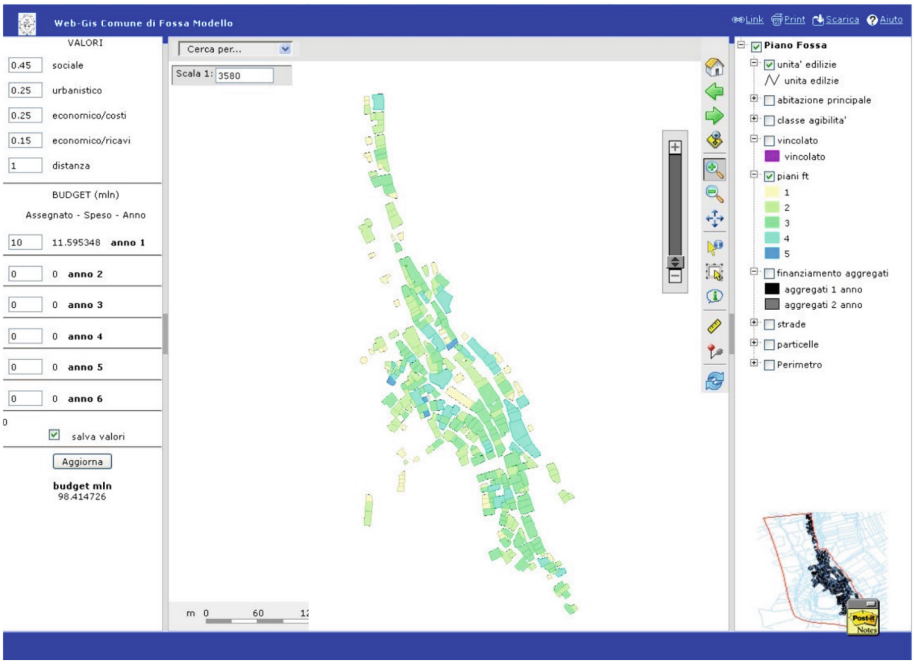


Fig. 6. The Web-GIS query-planning interface.

4 Application and Results

By implementing the parameters that generate multiple scenarios, it is possible to display and compare the six scenarios for the allocation of resources in space and time over the 6-year period envisaged according to a static approach that carries out the trade-off

between qualitative criteria (equity and effectiveness) and quantitative criteria (efficiency and cost-effectiveness) according to the weighting system of Fig. 5 (columns 1–6).

Each of the six images in Fig. 7 shows the funding space-time allocation program in two different ways: the map highlights the reconstruction stages with dark-to-light shading (first year dark blue, second year light blue, … sixth year yellow); the graph lists all the 72 Bas in the rows, and the light blue marker in the columns indicates the placement of the BAs over the 6-year funding period.

The map comparison provides useful information on the space-time placement of each BA in the reconstruction, but above all on the spatial concentration of the reconstruction sites in each year, from the point of view of the best management of the process. The table comparison, in turn, provides information about the temporal concentration of the largest number of BAs, as well as the priority of the reconstruction of each BA, the latter measured as the times in which each BA is placed in each year over the six scenarios.

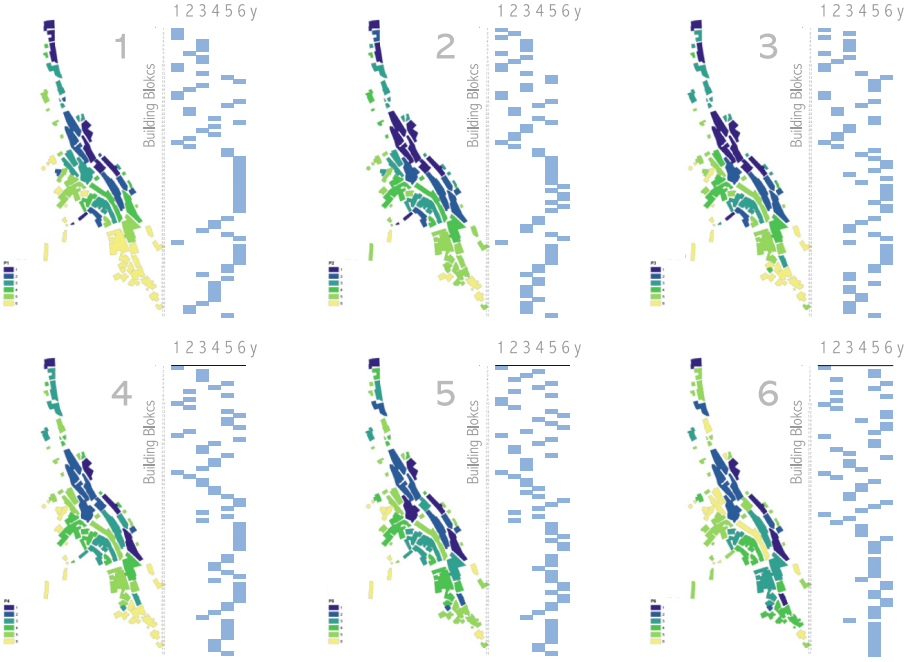


Fig. 7. Space-time funding allocation according to the static approach 1–6 strategies performing the trade-off between qualitative and quantitative criteria

The same comparison is displayed in Fig. 8 with reference to the dynamic approach and according to the hypothesis of a trade-off between qualitative and quantitative criteria (Fig. 5, columns 7–15). In the dynamic approach, the introduction of an additional criterion, "New centralities", generates three further scenarios.

Finally, Fig. 9 displays the comparison between scenarios in the dynamic approach according to the trade-off between the four original criteria and the new one concerning

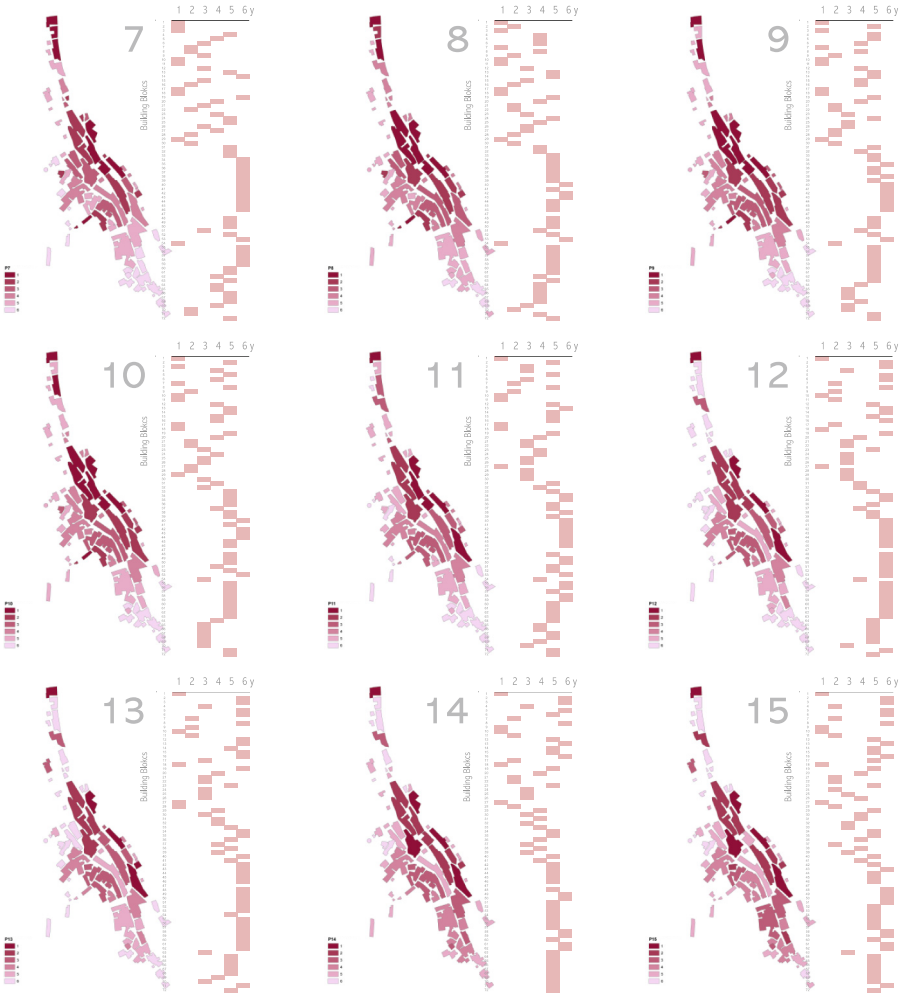


Fig. 8. Space-time allocation of resources according to nine dynamic approaches; the strategies 7–15 represent the trade-off between qualitative and quantitative criteria.

the progressive change of the location value of the BAs reconstructed year by year (Fig. 5, columns 16–24).

A whole synthetic view at the results of this space-time programming experiment allows us to recognize the overall priority that the central area deserves due to the convergence of the main value dimensions. Nevertheless, some BAs in this area are less prioritized due to the lack of main dwellings in them.

The overall results of the scenario comparison are presented in Fig. 10, which shows for each strategy (columns) the preference systems (the weights according the main general criteria and the added one), and the corresponding individual and aggregated scores, highlighting the preferred ones within each of the three approaches, Scenario

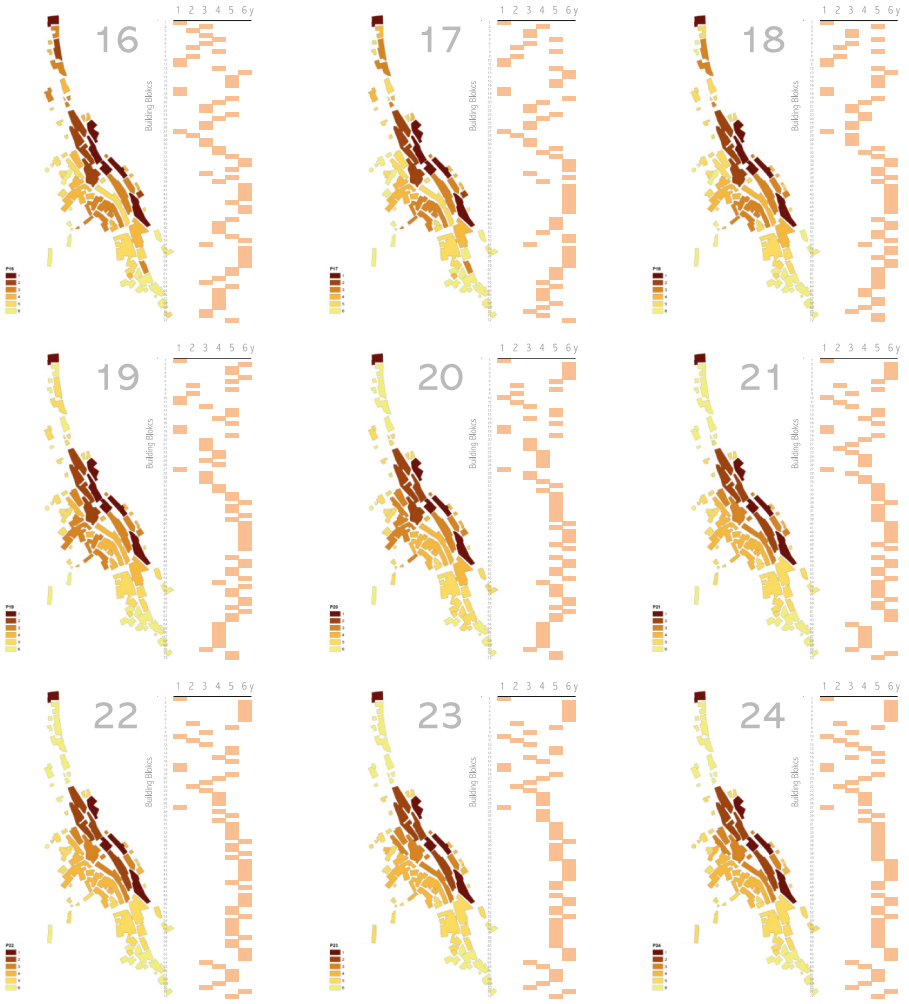


Fig. 9. Space-time allocation of resources according to nine dynamic approaches; the strategies 16–24 represent the trade-off between the four original criteria and the additional dynamic criterion.

2 in the static approach, Scenario 8 in the first dynamic approach, Scenario 16 in the second dynamic approach.

The results show the global inconsistency: the increasing weight of the New centrality criterion to the detriment of the others, as shown by the lowest and decreasing scores of the scenarios of the second dynamic approach.

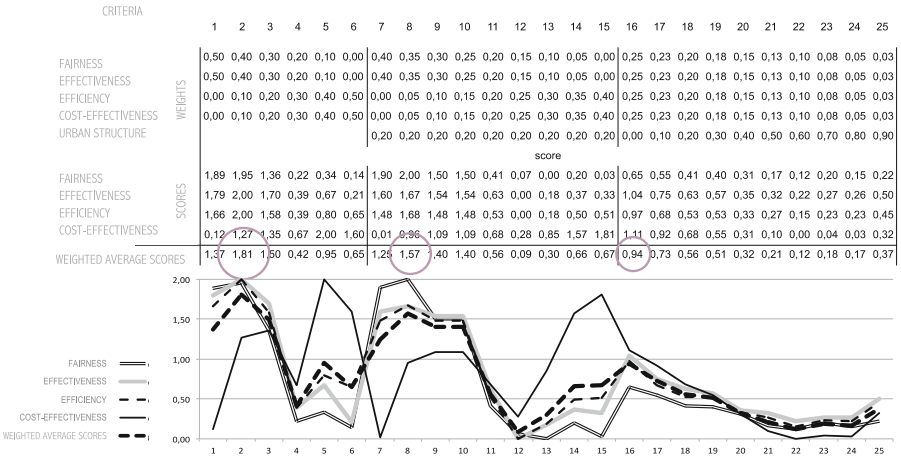


Fig. 10. Final comparison of the 24 scenarios by approaches.

5 Discussions and Conclusions

The proposed approach suggests some general and conceptual considerations concerning a science of valuation basic references.

Although the identification and, in a way, the "construction", of the best timetable seems to be the natural outcome of this heuristic experiment, the original research question of this experience doesn't concern "who is the winner".

In the decision-making approaches, the social agreement about the weights influences – and somehow constructs – the reality that fills our value judgements with truth.

In the social sciences, constructivism is a philosophical current according to which the reality of shared values is expressed in the autonomy of a self-conscious humanity to construct its own values rather than deriving them from some authority. "Constructivism has been criticised by Hayek, who sees it as a prejudice according to which the human beings who have created societies, institutions and civilisations legitimise themselves to change them at will according to their desires and aspirations. It is an attitude of those who are aware of the unintended consequences of deliberate actions and who seek a rational reconstruction of society and institutions, as is typically assumed in utopian scientism" [20].

Although this kind of reality is a social reality, it's not implicitly a "reality of values" that is the fair combination of the axiological (individual) and the ethical (collective) dimensions of value. Decision-makers, as well as people contingently involved, might not be able to consider some issues and dimensions of the value as they actually should be considered authentically, i.e. outside of contingency. Accordingly, construction should be on the one hand limited, on the one hand extended – i.e. "contextualized".

Contextualism could, therefore, be the philosophical perspective to relate this dual and apparently contradictory condition of validity of multi-perspective judgements to the reconstruction scenarios that determine the fate of peoples and territories.

Among the many definitions and perspectives of contextualism, the following seems to be the most appropriate to our purposes: "according to Wittgestein, contextualism is a model of epistemic justification that consists in legitimating beliefs through context. The context does not act as a self-justifying foundation of knowledge, but as an unjustified background to it" [21]. Therefore:

– according to the first dimension of limitation, the context can be taken as "the" overall and superordinate background of the validity of a chain of assumptions; for example, "a social system guaranties the sovereignty over just the body only within a liberal ethical-political conception, which ascribes to the person the character of full self-determination" [22]: the liberal conception doesn't need any justification, it is taken for granted;
– according to the second dimension, the context takes on a specific objectual and subjectual self-consistency: it is the "inertia" that characterizes the objects and their relations that make a place "that place". In this case, context delimits what really counts, and as such context is the subject of "what is owed to people and things, that is, what people and communities are responsible for" [23].

The above basic concepts has informed the development of the proposed conceptual model proposed (Fig. 2) and with reference to the following further and more specific considerations concerning the search for contextual self-consistency of an original, authentic and enduring home-city-landscape system. To this end, the Method of Oppositions can be used to better understand any concept in relation to its opposite. In order not to fall into the temptation of the "value relativism", the pairs of opposites were chosen from an axiological-ethical perspective, so that the subsequent is "undeniably better" than its antecedent. The terms of the following opposition (or groups of them) are present in the above model.

Unique vs Multiple, Quantity vs Quality: concerns the relationship in terms of value between homogeneous elementary units (BUs) and heterogeneous units (BAs). The latter have a social and administrative dimension transcending the former. Several assumptions have been made about the correct scoring construction of BAs composed of one, a few or many BUs, to represent the fair qualitative value attributed on the basis of quantitative variables.

Metrics vs Semantics, Indices vs Attributes: concerns the opposite placement of "reference" (the physical object like a BU) and "sign", the synthesis of the characteristics relevant to the cognitive process and the corresponding values relevant to communicative (comparative) action on it (the placement in the Timetable).

Things vs Goods: this opposition is consistent with the narrative that assumes market as the social place of the economic communication that transforms ("transcends") things into goods through of the abstract monetary measurement of their value [24].

Preferences vs Values: concerns the relationship between the individual perspective and the evaluation, the purpose of which is to transform subjective preferences into intersubjective value judgements; specifically, this opposition concerns the projection of the demand for performance implicitly expressed by the house and its relevance in the prospect of the building, urban, economic, social coherence of the reconstruction process (House/City matters!).

Facts vs Context, Semantic vs Syntaxes, Description vs Interpretation, Valuation vs Decision: with regard to the relationship between evaluation and programming, the single semantic merely supports the choices, while the global syntax coordinates the whole valuation and decision-making process; these opposites help to integrate the vertical comparisons between the characteristics and scores (semantics) of an urban phenomenon, as well as the horizontal comparisons (syntaxes) between all the phenomena.

Inflation vs Deflation, Information vs Communication: furthermore, a remarkable function of the model concerns the possibility of managing the Information-Communication Process: 1. to first inflate the information by generating many different layouts; 2. to then deflate this massive information by selecting the best ones, each of which within a specific dialogic context;

Space vs Time: this opposition extends into the future the contextuality of simple space and, consequently, the field of justification of the project.

Dis-order vs Order, Equilibrium vs Dis-equilibrium: the present experience is framed in a process of reconstruction aimed at transforming the Dis-order caused by the catastrophe into a new order that is inevitably different from the previous one. The new order must be based on a different kind of Dis-equilibrium, that is the necessary social tensions, in this case fed by people's reaction to the catastrophic situation, whose Equilibrium is the metaphor of thermodynamics.

Probable vs Possible, Process vs Event: these last oppositions converge towards the prospect (hope) of a new world creation. A Process is generally a gradual succession of facts that are strongly related to each other. An event is the effect that exceeds its own causes, so that: a process is somehow probable, an event is somehow possible.

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

References

1. Cappello, C., Giuffrida, S., Trovato, M.R., Ventura, V.: Environmental identities and the sustainable city. The green roof prospect for the ecological transition. Sustainability **14**, 12005. https://doi.org/10.3390/su141912005 (2022)
2. Dolce, M., Di Pasquale, G., Speranza, E.: A multipurpose method for seismic vulnerability assessment of urban areas. In: Proceedings of the 15th World Conference on Earthquake Engineering (WCEE), Lisboa, Portugal, 24–28 September (2012)
3. Trovato, M.R., Giuffrida, S.: The Protection of territory from the perspective of the intergenerational equity. In: Mondini, G., Fattinnanzi, E., Oppio, A., Bottero, M., Stanghellini, S. (eds.) SIEV 2016. GET, pp. 469–485. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-78271-3_37
4. Trovato, M.R., Nasca, L. An axiology of weak areas: the estimation of an index of abandonment for the definition of a cognitive tool to support the enhancement of inland areas in Sicily. Land **11**, 2268 (2022). https://doi.org/10.3390/land11122268
5. Trovato, M.R.: Human capital approach in the economic assessment of interventions for the reduction of seismic vulnerability in historic centres. Sustainability **12**, 8059 (2020). https://doi.org/10.3390/su12198059 (2020)
6. Carreno, M.L., Cardona, O., Barbat, A.H.: Urban seismic risk evaluation: a holistic approach. Nat. Hazard. **40**, 137–172 (2007)

7. Italian Government: Ministry, Decree n.352 – National Recovery and Resilience Plan (2021)
8. Giuffrida, S., Gagliano, F., Tocci, C.: Emergency limit condition in the old towns. Axiology of seismic vulnerability and design. Valori Valutazioni **15**, 55–67 (2015)
9. Delegate Commissioner for Reconstruction: Advancement state and planning. 15/03/1012 Update (2012)
10. Grant, D.N., Bommer, J.J., Pinho, R., Calvi, G.M., Goretti, A., Meroni, F.A.: Schema di prioritizzazione per l'intervento sismico negli edifici scolastici in Italia. Earthq. Spectra **23**, 291–314 (2012)
11. Belton, V.: Interactive multiobjective optimization from a learning perspective. In: Branke, J., et al. (eds.) Multiobjective Optimization: Interactive and Evolutionary Approaches, Springer, Heidelberg (2008)
12. Giuffrida, S., Napoli, G., Trovato, M.R.: Industrial areas and the city. Equalization and compensation in a value-oriented allocation pattern. In: Gervasi, O., et al. (eds.) ICCSA 2016. LNCS, vol. 9789, pp. 79–94. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-42089-9_6
13. Malczewsky, J.: GIS and Multicriteria Decision Analysis. John Wiley, Hardcover (1999)
14. Trovato, M.R., Clienti, C., Giuffrida, S.: People and the city: urban fragility and the real estate-scape in a Neighborhood of Catania, Italy. Sustainability **12**, 5409 (2020). https://doi.org/10.3390/su12135409
15. Andeani F., Carocci, C.F.: Urban fabric, construction types and the art of city-building. Approaches and methods for postearthquake recontruction plans. IJPP Italian J. Plan. Pract. **III**(1) (2013)
16. Comes, T., Wungaards, N., Shultzmann, F.: Intelligent technologies for decision support and preference modelling, in: Doumpos, M., et al. (eds.) Multiple Criteria Decision Aid and Artificial Intelligence. Wiley, United Kingdom (2013)
17. Dyer, J.: MAUT. In: Figueira, J.R., et al. (eds.) Multiple Criteria Decsion Analysis: State of the Art Surveys, pp. 265–295, pp. 507–563. Springer, Berlin (2005)
18. Carocci, C.F.: Piani di Ricostruzione post-sisma tra conservazione e rigenerazione Urbana. I casi di Villa Sant'Angelo e Fossa (AQ). In: Castagneto, F., Fiore, V. (eds.) Recupero, Valorizzazione, Manutenzione Nei Centri Storici, Lettera Ventidue, Siracusa, pp. 114–117 (2013)
19. Carbonara, S.: Il sisma abruzzese del 2009: la previsione di spesa per la ricostruzione. Valori e valutazioni **11**, 67–85 (2013)
20. Fornero, G.: Costruttivismo. In: Abbagnano, N. (ed.) Dizionario di filosofia, Utet, Torino (2008a)
21. Fornero, G.: Contestualismo. In: Abbagnano, N. (ed.) Dizionario di Filosofia, Utet, Torino (2008)
22. Villa, V.: Contestualismo e teoria dell'interpretazione. Risposte ai miei critici. Diritto e questioni pubbliche, Palermo (2013)
23. De Monticelli, R.: La questione civile. Raffaello Cortina (2011)
24. Dan, M.B.: Decision making based on benefit-costs analysis: costs of preventive retrofit versus costs of repair after earthquake hazards. Sustainability **10**, 1537 (2018)



The Urban Life Cycle in the Italian Demographic Winter. An Analysis on Metropolitan Cities

Giuseppe Borruso[1(✉)] and Ginevra Balletto[2]

[1] DEAMS - Department of Economics, Business, Mathematics and Statistics "Bruno de Finetti", University of Trieste, Via A. Valerio 4/1, 34127 Trieste, Italy
giuseppe.borruso@deams.units.it

[2] DICAAR - Department of Civil, Environmental Engineering and Architecture, University of Cagliari, Via Marengo 2, 09123 Cagliari, Italy
balletto@unica.it

Abstract. Since their foundations, cities configured themselves as places of innovation, where flows of people, goods, services, ideas, culture, met and, through interaction allowed spreading of new ideas, solutions, applications. The traditional, spontaneous, way of spreading of innovation has recently left the pace to more structured systems. To-date, innovation is part of structured and prepared business models in enterprises, and it is very often rooted into policies of local, regional, and national development. Cities are not an exception to that, and investment on innovative systems and methods can make the difference in the success or failure of cities. Following the literature on urban geography dealing with the urban life cycle, covering also the most recent evolutions, summarized, as a matter of example, in Florida's 'New Urban Crisis', the present work aims at observing the most recent urban dynamics between spatial, urban demographic changes in view of the 'demographic winter' that Italy, together with many industrialized and more mature economies, is experimenting. The work analyses the Italian urban system, considering the urban dynamics in terms of population change, in its different administrative and functional aggregations, observing their characteristics and evolutions in recent times (2019–2023, pre and post Covid-19 pandemics), highlighting the formation of urban 'champions' and proposing a spatial analysis observing and evaluating their characteristics in terms of population dynamics.

Keywords: Cities · Demographic Transition · Urban Planning · Regional Planning

1 Introduction

From the very beginning of times in which humans started to settle in fixed locations, cities were developed as a consequence of a massive innovation as the introduction of agriculture, what brought with it an entire set of innovative by-products, as, as a matter of instance, the organization of an urban society, with well-defined ranks and

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 159–171, 2024.
https://doi.org/10.1007/978-3-031-65238-7_11

roles; the introduction of writing and mapping, for storage and warehousing purposes, the realization of ad-hoc buildings for the different purposes and functions played by the new organization of society and economy. The innovations in cities of course are wider than those mentioned above, however, from the very beginning of their existence, and from the dawn of time, cities have become important places of interaction, where flows of people, goods, ideas and, more generally, novelties - these including conflicts, wars, epidemics - easily met, helped by the nature of cities themselves to concentrate these elements in a relatively limited amount of space. Density and interaction therefore characterize cities heavily as human made artifacts and as an important physical and socio-economical expression and footprint of civilizations [1–3].

The research is aimed at analyzing the population dynamics in the main Italian metropolitan cities (in administrative terms) and areas (in functional ones), examining as well as the performances in the recent pre and post pandemic (2019–2023) years. The research has the aim to mapping the dynamics of the urban population in Italy, forced between depopulation, ageing of the population and urban sprawl, correlated to the increase in accessibility and property value.

The rest of the paper is organized as it follows. Paragraph 2 provides a conceptual review of the urban lifecycle and the demographic aspects related to that. Paragraph 3 describes the study area analyzed (Italy), the data (population and innovation indicators) and the methods (the application of the urban life cycle model together with a local analysis based on spatial autocorrelation techniques among elements of innovation). In Paragraph 4 results and discussion are presented, while Conclusions in Paragraph 5 provides a general overview of the main findings of the paper, shading light to the next research agenda to be implemented.

2 The Urban Lifecycle and Demography. A Review

From the dawn of time, cities have been important places of interaction, exchange of flows of people, goods, ideas, culture, and, more generally, and in geographical terms, innovation. In this sense innovation represents ‘something new’, not present before. Still in geographical terms, innovation can be either something coming out from the process of interaction among places, i.e., moving from one place of origin to a set of destinations, and therefore part of the differences in places in terms of the peculiarities characterizing single locations in space, or as the outcome of a local process of interaction. Being cities dense environments, in which the above-mentioned elements as people, goods, ideas and culture meet, they always represented a fertile environment for the development of creativity and innovations [4, 5].

In literature, the observation of the evolution of cities in their relationship with the related region-territory, has led scholars to model the so-called ‘Urban Life Cycle’ [6, 7]. In this sense, the urban life cycle model can be useful in understanding the basics of the core-periphery – or core-ring – relationship and to understand urban population dynamics [8–10]. The standard well-established model foreseen different steps that cities are likely to follow during their existence. In such a sense the model considers different parts a city consists of, as its core and its ring, or inner periphery. Furthermore, the model in its evolution considers the metropolitan city as a whole. Extra-elements as the urban

extra-peripheral fringes can be considered. According to Van den Berg et al. [7] a city passes through an organism through an urban life cycle that follows four different stages, regarding the two main components of a city: its core and its fringe (or ring). The urban life cycle is not an obliged path a city must follow, but a possible model a city could take, in different five stages not necessarily determined (Fig. 1a).

The first stage of urbanization regards a concentration in the core and reduction of density in the ring. This is the early stage of creation and growth of cities as relevant settlements with increasing levels of agglomeration. This is also the stage in which density is increasing, both in the core and, in a second substage, in the ring.

The second stage is that of suburbanization and is characterized by a slower increase in the core and an increase of agglomeration in the ring, but with a decreasing pace in the second substage in both areas. This is the stage that industrialized countries experimented with the introduction of cars and private transport that rapidly helped the increase in size of the city in its extension, thus reducing density and the presence of resident people in the city center, this latter becoming an area dedicated today /working-time activities and with the presence of city users. This process is also generally coupled with an increase of urban rent in the center, which helps the centrifugal relocation of residents in the suburbs in the ring.

The third stage is that of disurbanization and is characterized by an agglomeration decreases in both the core and in the ring; overall the city and its first ring of suburbs reduce their population and density. Disurbanization can occur for different reasons, as the loss of role of the main city - as it did occur to many industrial city because of deindustrialization - Detroit being the most fitting example -, the overall decrease of the population in the area for natural cases - as for an overall decrease of the population of the entire area if not of the country -, and, still, for a further centrifugal jump of the population towards farther neighborhoods, suburbs or satellite cities in the 'second ring'. According to the different patterns, disurbanization can be either observed together with important increases of urban rent - and therefore a further relocation of people farther from the center or, on the contrary, a reduction of rents due to a 'lack of desire' for central locations, in cases in which a city lose its main function and attractiveness.

The four stage is that of reurbanization and is characterized by of the process of going back to the city center - back to downtown or back to the core - as the effect of a rediscover of the city centers, initially by a creative class - as initially theorized by Florida [11] - gradually substituted by - generally - more affluent residents.

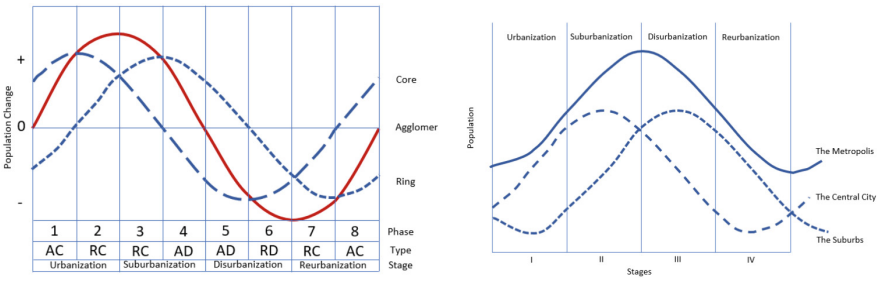


Fig. 1. a) The urban life cycle, b) The urban life cycle in a metropolitan area. Source: [7, 12]

The urban lifecycle paradox is that of the spreading of the urban lifestyle over a wider and wider area - if we not consider just agglomeration but the overall population distribution on what can be defined as 'urban' (Fig. 1b) - together with a gradual and constant reduction of one of the main character of the city itself, as its density, or agglomeration, or, still, concentration of people, buildings and activities that characterize the functions and reasons of existence of the city itself. Such a reduction of the residential population density, however, is coupled with an increase of the flows and interactions - particularly in the sense of commuting of city-workers from farther destinations to the city centers - as well as an overall mix of residents and city users in the core [13–16].

3 The Study Area, Data and Method

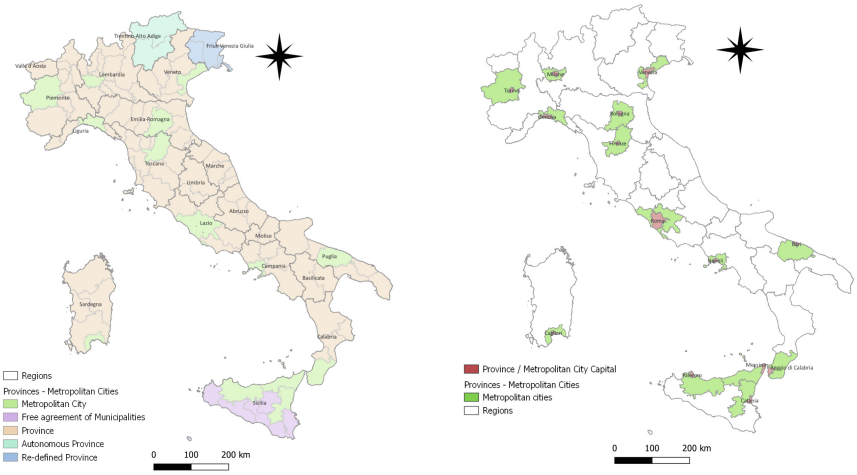
3.1 The Study Area

The analysis is performed considering Italy as the study area. The attention is particularly drawn over the administrative and statistical subdivision of Provinces and similar - i.e., Metropolitan cities, where they are present in the administrative layout - and the capital municipalities of these units. Furthermore, the analysis is performed considering the FUAs - Functional Urban Areas - related to the metropolitan Cities to consider both the administrative and the functional principles of metropolises [17, 18].

From the administrative and statistical point of view, Italy is organized in three different levels, these corresponding to macro, intermediate and micro levels of administrations, corresponding to Regions, Provinces / Metropolitan cities / aggregations of Municipalities, and Municipalities. Regions hold a high level of autonomy, delegated from the central state to issue laws particularly on matters related to health, transport and spatial planning selected aspects, in a form of loose federal state. Municipalities oversee regulating laws on local taxation, economic activities, and planning, in line with the national and regional laws and orientations. Provinces acted as the intermediate administrative level in the past, and more recently their role has become mainly as that of an intermediate strategic planning to be harmonized with the lower and upper levels, with several differences between the different regional frameworks in which provinces are inserted. The main change in the intermediate level took place after 2014 (law 7 April 2014, n. 56, so-called 'Delrio law') with the transformation of the provinces centered around the main urban municipalities into metropolitan cities.

These units in most of the cases - Cagliari represents an exception - occupy the same areas of the former provinces, holding, therefore, more administrative meanings than a functional one. Fourteen metropolitan cities were defined by the national reform law, allowing, however, the Italian five autonomous regions (Sicily, Sardinia, Val D'Aosta, Trentino Alto Adige with the Autonomous Provinces of Trento and Bolzano, and Friuli Venezia Giulia) the possibility of defining regional metropolitan cities on their own, thanks to the autonomy granted in terms of spatial planning and internal administrative organization (Fig. 2). A vast literature has been produced through the years analyzing and commenting the Italian political geography of its administrative units, from their basic foundations and characteristics [19–21], examining the relationships between the different levels of administration and the roles, powers and planning tools assigned to them [22, 23] particularly in light of the most recent evolutions of the intermediate level

of administration and revision towards the metropolitan cities [24–27]. The metropolitan cities were considered also in terms of their functional areas (FUAs) and the municipalities included into the core and ring areas of these latter units (Fig. 3, [28, 29]). The debate among the consideration of metropolitan cities and areas has been and is wide and deep, covering, with reference to the Italian case, the functional aspects [21, 22, 30–33].



a) b)

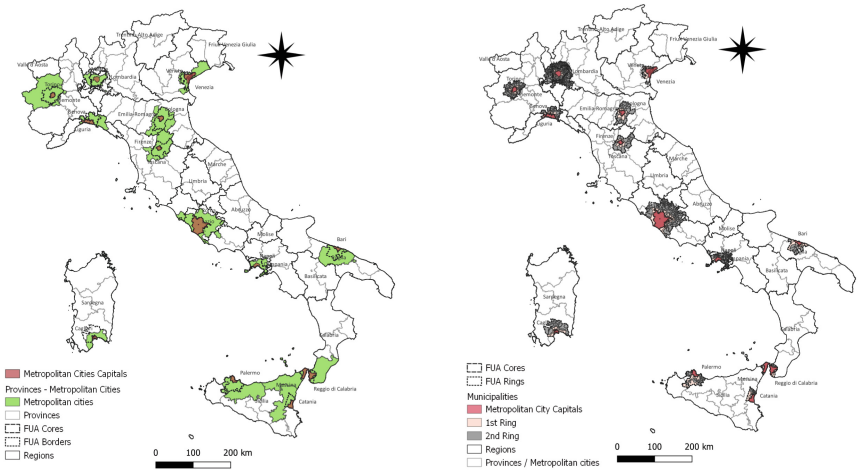
Fig. 2. a) Administrative divisions: Regions, Metropolitan Cities and Provinces; b) Regions, Metropolitan Cities and their Capital Municipalities; Author: G Borruso, data from ISTAT [35].

3.2 Data

The data considered in this analysis were taken from different sources and particularly referred to major categories, these belonging to demographic elements, through their evolution in time, as highlighted in Table 1.

The analysis has been carried on considering the Italian administrative divisions in Provinces and Municipalities. Population data were attributed to Municipalities, these latter considered with references to metropolitan cities and areas. We considered a comparison over a 5-year period, between 2019 and 2023. This timeframe was considered to observe changes over a narrow period and well distant from the national census of 2011 and 2021. Data were obtained from Italian National Statistic Institute (ISTAT) in the different years [33, 34], together with geographical data for administrative units (municipalities, provinces / metropolitan cities / intermediate units, regions [35]).

Population data at Municipal level were made uniform to the administrative divisions of 2023. The administrative geography of Italy has in fact changed during the recent years, with municipalities alternatively merging or splitting, or changing their provincial belonging. Also, the intermediate level of Provinces, in recent years considered more for statistical purposes than for administrative ones, passed through several



a) b)

Fig. 3. a) FUAs: Metropolitan Cities and their FUAs; b) Metropolitan cities' FUAs and their municipalities. Author: G. Borruso, data from ISTAT [35], OECD and Copernicus [36].

Table 1. The data used.

Data	Indicators	Spatial Units	Source
Population	Population density Population change (2019–2023)	Municipalities; Provinces/ Metropolitan Cities FUAs	ISTAT; OECD; Copernicus

reforms and reconfigurations, very often varying their borders. In such a framework, population data in 2019 were reconfigured and attributed to the 2023 administrative units. Doing so allowed us to compare the two different periods easily and correctly. FUAs were obtained from Copernicus Data and according to the OECD methods proposed for defining homogeneous metropolitan areas at international level, based on a minimal dimension (50,000 inhabitants), population density and commuting [28, 29]. Data attributed to municipalities were aggregated considering different belongings to FUA's cores and rings to attribute population data to such non-statistical and administrative units.

Demographic data were particularly considered for an analysis on population and the changes occurred within metropolitan and urban areas.

3.3 Methods

The analysis has been performed considering the urban life cycle model applied to Italian cities, considering the spatial variation of population over a 5-years period (2019–23) in the Italian Municipalities, with particular reference to those belonging to the main urban

areas (metropolitan cities and areas).To analyze the urban pattern and changes occurring in the period, the population in the two years analyzed was attributed to municipalities in their 2023 configuration to monitor the changes occurred in the period considered. Furthermore, the analysis was performed with reference to the Italian metropolitan cities and their areas. As the areas covered by the metropolitan cities are generally following an administrative principle and logic, it was decided to integrate such spatial units with their related data with the FUAs, as defined by OECD - EU and derived from the Copernicus database [18, 36, 37].

4 Results and Discussion

The analysis was performed on the fourteen Metropolitan Cities as officially recognized from an administrative point of view by Italian law. These cities were analyzed in different terms from the point of view of the population changes. With reference to these 'metropolises', we considered their population dynamics, considering different official statistical units. In particular, the following assumptions and steps were followed.

When considering population data, we referred to Metropolitan Cities and Functional Urban Areas (FUAs).

The Metropolitan City capitals were considered as the 'central' municipalities of the Metropolitan City areas.

When considering the Metropolitan Cities, the homonymous administrative and statistical areas were considered.

When considering the Metropolitan Areas in functional terms, we considered the FUAs' areas and the municipalities belonging to them.

For each Metropolitan City, we considered its homologous FUA.

The external borders of FUAs were chosen to collect all the municipalities belonging to a certain Metropolitan City / Area.

The analysis on the core/ring was done considering two different situations (in both cases:

1. Based on administrative divisions: Metropolitan Capital, First Ring Municipalities (adjacent to the Metropolitan Capital), Second Ring Municipalities - adjacent to the First Ring Municipalities.
2. Based on the FUA's definition method: Urban Core - 'central' municipalities, including Metropolitan Capital; Ring - other Municipalities, external from the Core and within the FUA's border.

An initial consideration to be done regards the delimitation of the Metropolitan Cities as in the Italian law and its (lack of) relationship with their functions in metropolitan terms [38]. The 14 cities considered are the biggest in Italy, nonetheless the delimitation of their 'catchment areas' follow administrative principles rather than functional ones. Nonetheless they represent an important share of the Italian population. The municipalities of the fourteen Metropolitan Capitals together count for 9.2 million people over a total of 59 million people living in Italy in 2023, while their Metropolitan City areas count for 21.3 million people [33]. The administrative-based system of definition of

the Italian Metropolitan City areas was therefore integrated with the functional one, developed for the definition of European Functional Urban Areas.

In absolute terms, the population involved in the two systems is quite similar – 21.3 million people in metropolitan cities; 20.4 million people in FUAs in 2023 - although their spatial pattern is quite dissimilar. Examples of that can be noticed in Fig. 4, with a sample of the major Metropolitan cities and areas considered. In some cases - i.e., Rome, Naples - the functional and administrative dimensions are quite similar. On the contrary, in the case of Milan the Metropolitan City is just part of the central core of the FUA, while in the case of Bari the Metropolitan City area is much bigger than the functional one. In most cases, the Municipality of the Metropolitan City Capital is also the core of the FUA, apart from the cases of Milan and Naples, where the urban core includes other municipalities than the Metropolitan City Capital.

The analysis required, as mentioned, a data harmonization between 2019 and 2023 in terms of the population attributed to municipalities and their provinces/metropolitan cities. Furthermore, spatial analyses were performed to obtain the municipalities enclosed within the FUAs and derive their belonging to the first and second rings of proximity (Fig. 4, areas in pink and grey) and their belonging to the core (dashed black line) or external FUA's borders (dotted black line).

The analysis on the population data on the two selected years displays an overall decrease of Italian population from 2019 to 2023 of −1.37%. Metro cities (administrative

Table 2. Population changes 2019–2023 (based on Municipalities data). Author: G Borruso, elaboration from ISTAT Data [33, 34] and OECD Data [36].

Metro Name	Metro City	Capital City	1st Ring	2nd Ring	FUA Core	FUA Ring	FUA Total
Torino	−1.52	−1.56	−1.75	−0.77	−1.56	−1.23	−1.39
Genova	−1.75	−1.40	−3.17	−3.41	−1.40	−3.29	−1.74
Milano	−0.68	−2.69	0.66	0.74	−0.66	0.62	−0.20
Venezia	−1.78	−3.48	−0.38	−1.23	−3.48	−0.61	−2.08
Bologna	−0.34	−1.03	0.46	0.93	−1.03	0.70	−0.20
Firenze	−1.08	−1.93	−0.24	−0.84	−1.93	−0.53	−1.22
Roma	−0.86	−2.30	2.79	1.42	−2.30	2.08	−0.77
Napoli	−2.23	−3.86	−1.42	−1.20	−2.25	−1.27	−1.99
Bari	−0.81	0.08	−1.33	−1.16	0.08	−1.26	−0.68
Reggio di Calabria	−3.32	−2.90	−4.71	−6.14	−2.90	−4.78	−3.22
Palermo	−2.23	−3.10	1.48	0.21	−3.10	0.68	−1.77
Messina	−3.00	−4.31	−2.67	−3.51	−4.31	−2.97	−4.14
Catania	−0.26	0.66	0.62	2.43	0.66	1.30	1.00
Cagliari	−0.88	−2.12	−0.40	−1.14	−2.12	−0.67	−1.12

areas) displayed a similar decrease of −1.32%, while metro areas (FUAs) represented lower figures (−1.01%). Quite different are the internal dynamics of the metro cities and areas (Table 2).

All the metropolitan cities and areas in total decrease their population. Most of the metropolitan cities and areas present an overall decrease of the center (metro capital in administrative terms) and the first and second rings of municipalities, as well in the functional separation of core area and ring area (Turin, Genoa, Venice, Florence, Naples, Reggio di Calabria, Messina, and Cagliari).

Milan, Bologna, Rome, and Palermo present an important decrease of the central municipalities and functional cores and an increase of the first and second rings, as well as of the functional ring areas. Bari, in Southern Italy, presents a slight increase of the central municipality and core, and a decrease of the external rings. Catania, albeit decreasing its overall metro population, witnesses an increase of the central municipality and of the rings. In functional terms, it is the only metro area to increase its population.

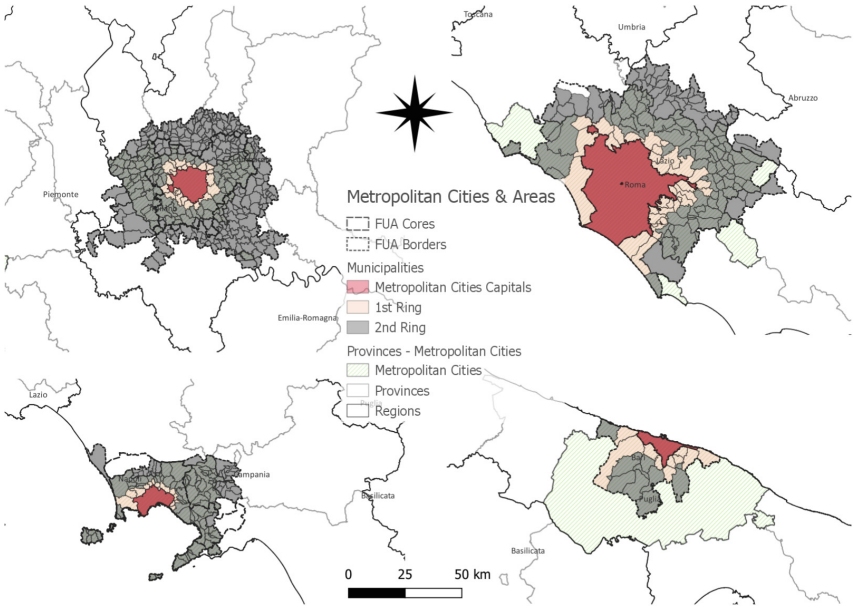


Fig. 4. Overview of a selected set of Metropolitan Cities and their FUAs. From Left to right, upper corner to lower corner: Milan, Rome, Naples, Bari. Author: G Borruso, elaboration from ISTAT Data [33, 34] and OECD Data [36].

It is worth stressing again that there is a difference in the shapes and areas of FUAs and metropolitan cities. As a matter of example, the metropolitan cities of Turin, Palermo, Catania, Messina, Reggio di Calabria, and Bari are considerably bigger than those of their FUAs. In such a sense, many Italian metropolitan cities cover not only the cores and rings, but also municipalities external to such areas. On the contrary, cities such as Milan - as the center of the Po Valley Megalopolis - and Cagliari - most important center

of Sardinia Island and region - are characterized by metropolitan cities smaller in size with respect to their FUAs.

Synthetizing data with reference to the urban life cycle scheme, Italian metropolitan areas can be observed as being mainly in the stages of disurbanization (third stage), apart from the two cities of Milan and Bologna, being still considerable in the latest fringes of suburbanization, and Bari and Catania, in a reurbanization (fourth stage) (Table 3).

Table 3. Urbanization, urban life cycle and Italian metropolitan cities & areas (2019–2023). Author: G Borruso, data from ISTAT Data [33, 34] and OECD Data [36] and Van den Berg et al. [7].

Stage	Sub-stage	Core	Ring	Agglomeration	City
Urbanization	1) absolute concentration	++	−	+	
	2) relative concentration	++	+	+++	
Suburbanization	3) relative deconcentration	+	++	+++	
	4) absolute deconcentration	−	++	+	Milan, Bologna
Disurbanization	5) absolute deconcentration	−−	+	−	Rome, Palermo
	6) relative deconcentration	−−	−	−−−	Turin, Venice, Genoa, Florence, Reggio Calabria, Messina, Cagliari
Reurbanization	7) relative concentration	−	−−	−−−	
	8) absolute concentration	+	−−	−	Bari, Catania

5 Conclusions

The analysis carried out in the present paper displays some interesting trends and characters of the main Italian urban areas. These spans from considerations about the on-going depopulation in the country, through to the difficulties of defining and delimiting urban areas in administrative and functional terms, through to the dubitative consideration of innovation as a driver in cities' performances and - therefore - as a driver of attraction.

One consideration must be referred to the relationship between the administrative and urban level of metropolitan cities and areas. The 14 metropolitan cities identified by the Italian law, with little exception follow their respective older provinces' borders, and are very different in terms of the surface covered. If the total amount of population

living in metropolitan cities is very close to that of their functional urban areas, important differences can be spotted. In cities like Milan and Cagliari, the metropolitan cities' areas - defined from the administrative point of view - are smaller than the Functional Urban Areas, that correspond to the metropolitan areas particularly from the commuting point of view. Many other metropolitan cities cover areas much wider than those covered by the FUAs, de facto including municipalities not strictly functionally related to the capital cities themselves.

This happens in Northwestern Italian metro cities like Turin and Genoa, as well as in the Southern ones such as Palermo, Catania, Messina, and Reggio di Calabria. The effect is twofold. On one side 'natural' metropolitan areas - as Milan and Cagliari - are underestimated in their administrative definition, while in other ones, the metropolitan cities govern over non strictly urban areas, playing therefore a role as 'micro regions', albeit in the Italian administrative framework the governance level is weaker if compared to those of Regions and Municipalities. Some reflections should therefore arise in terms of the more effective spatial design and pattern drawn by the administrative and functional levels.

The population dynamics present different behaviors and patterns in the selected period. In summary, the metropolitan cities and areas present peculiarities considering the urban life cycle and considering the issue of depopulation at present affecting Italy in particular. Albeit metropolitan cities present overall a similar trend in population decrease, their FUAs limit this if compared to the national values. Most of the cities considered can be at present considered spanning through the latest stages of suburbanization and those of disurbanization, particularly with a general decrease in the core municipalities, an increase in the rings in the suburbanizing ones - Milan and Bologna - and decrease in the disurbanizing ones. Few cities present a situation of reurbanization - Bari and Catania.

The research is therefore still open and requires in-depth analysis on various aspects for future research. On the one hand, the analysis of the geo-spatial distribution of the population poses a new question, namely what role innovation plays on demographic dynamics. An in-depth analysis should therefore be carried out on this to complete the analysis concluded so far. On the other hand, the role of intervening factors can be important in better understanding the phenomenon. Delving into the aspect of innovation could help to better understand the more complex dynamics and possible evolutionary paths that cities will probably follow in the years to come [39–42].

Acknowledgments. The paper represents the outcome of the joint efforts and aims of the two authors. Ginevra Balletto however wrote paragraphs 1 and 5, while Giuseppe Borruso wrote paragraphs 2, 3 and 4.

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

References

1. Sato, Y., Yamamoto, K.: Population concentration, urbanization, and demographic transition. J. Urban Econ. **58**, 45–61 (2005)

2. Cividino, S., Halbac-Cotoara-Zamfir, R., Salvati, L.: Revisiting the "City Life Cycle": global urbanization and implications for regional development. Sustainability **12**(3), 1151 (2020)
3. McCann, P.: Urban futures, population ageing and demographic decline. Camb. J. Reg. Econ. Soc. **10**(3), 543–557 (2017)
4. Saleh, R., Brem, A.: Creativity for sustainability: An integrative literature review. J. Clean. Prod. **388**, 135848 (2023)
5. Cohen, B.: Urbanization in developing countries: current trends, future projections, and key challenges for sustainability. Technol. Soc. **28**(1,2), 63–80 (2006)
6. Alonso, W.: A theory of the urban land market. Pap. Reg. Sci. **6**(1), 149–157 (1960)
7. Van den Berg, L., Roy Drewett, R., Klaassen, L.H.: A Study of Growth and Decline, Urban Europe, vol. 1. Pergamon Press, Oxford (1982)
8. Koomen, E., Van Bemmel, M.S., Van Huijstee, J., Andrée, B.P.J., Ferdinand, P.A., Van Rijn, F.J.A.: An integrated global model of local urban development and population change. Comput. Environ. Urban Syst. **100**, 101935 (2023)
9. Seyedabadi, M.R., Eicker, U.: A critical review of urban scale life cycle assessment of the built environment. Sustain. Analyt. Model. **3**, 100026 (2023)
10. Dyson, T.: The role of the demographic transition in the process of urbanization. Popul. Dev. Rev. **37**, 34–54 (2011)
11. Florida, R.: The new urban crisis: how our cities are increasing inequality, deepening segregation, and failing the middle class-and what we can do about it. London: Hachette UK, London (2017)
12. Egidi, G., Cividino, S., Vinci, S., Sateriano, A., Salvia, R.: Towards local forms of sprawl: a brief reflection on mediterranean urbanization. Sustainability. **12**(2), 582 (2020)
13. Henderson, J.V., Venables, A.J.: The dynamics of city formation. Rev. Econ. Dyn. **12**(2), 233–254 (2009)
14. Cuthbert, A. R.: The Form of Cities: Political Economy and Urban Design. Wiley (2008)
15. Borruso, G., Balletto, G.: The image of the smart city: new challenges. Urban Sci. **6**(1), 5 (2022)
16. Bezrukikh, V.A., Kuznetsova, O.A., Ligaeva, N.A., Makarova, L.G.: Current systems of protected areas integrated with urban agglomerations. IOP Conf. Ser.- Mat. Sci. Eng. **463**(4), 042055 (2018)
17. OECD Functional Urban Areas. https://www.oecd.org/regional/regional-statistics/functional-urban-areas.htm. Accessed 05 May 2024
18. Schiavina, M., et al.: Land use efficiency of functional urban areas: global pattern and evolution of development trajectories. Habitat Int. **123**, 102543 (2022)
19. Sestini, A.: Le regioni italiane come base geografica della struttura dello stato. In: AA.VV. (eds.) Atti del XIV Congresso Geografico Italiano, pp. 128–143. Zanichelli, Bologna (1949)
20. Gambi, L: L'equivoco fra compartimenti statistici e regioni costituzionali. Lega, Faenza (1963)
21. Cori, B.: Geografia Urbana. Utet, Torino (2006)
22. Memoli, M., Governa, F. (eds.): Geografia dell'Urbano. Spazi, politiche, pratiche della città. Carocci, Roma (2011)
23. Donolo, C.: Sul governo possibile delle città. In: Dematteis, G. (ed.) Le grandi città italiane. Società e territori da ricomporre, pp. 175–206. Marsilio, Venezia (2012)
24. Castelnovi, M. (ed.): Il riordino territoriale dello Stato. Riflessioni e proposte della geografia italiana. Società Geografica Italiana, Roma (2013)
25. Dini, F., Zilli, S. (eds.): Il riordino territoriale dello Stato. Società Geografica Italiana, Roma (2015)
26. Benetazzo, C.: Le Province a cinque anni dalla legge "Delrio": profili partecipativi e funzionali organizzativi. Federalismi.it **5**, 2–49 (2019)

27. Dini, F., Zilli, S.: Neo centralismo e territorio fra Città metropolitane, aree vaste e intercomunalità. Introduzione. In: Salvatori, F. (ed.): L'apporto della Geografia fra rivoluzioni e riforme, pp. 2213–2218. AGeI, Roma (2019)
28. OECD: Redefining "Urban": A New Way to Measure Metropolitan Areas. OECD Publishing, Paris (2012)
29. Dijkstra, L., Poelman, H., Veneri P.: The EU-OECD definition of a functional urban area. OECD Regional Development Working Papers, 11 OECD Publishing, Paris (2019)
30. Scaramellini, G.: Funzioni centrali, funzioni metropolitane, reti urbane. Franco Angeli, Milano (1990)
31. Crisci, M., Gemmiti, R., Proietti, E., Violante, A.: Urban sprawl e shrinking cities in Italia. Trasformazione urbana e redistribuzione della popolazione nelle aree metropolitane, IRES, CNR (2014)
32. Turri, E.: La megalopoli padana. Marsilio, Padova (2000)
33. ISTAT, Demografia in cifre, Popolazione residente per sesso, età e stato civile al 1° gennaio 2023. https://demo.istat.it/app/?i=POS&l=it. Accessed 05 May 2024
34. ISTAT, Demografia in cifre, Popolazione residente per sesso, età e stato civile al 1° gennaio 2019, https://demo.istat.it/app/?l=it&a=2019&i=POS. Accessed 05 May 2024
35. ISTAT, BASI TERRITORIALI E VARIABILI CENSUARIE, https://www.istat.it/it/archivio/104317. Accessed 05 May 2024
36. OECD European Commission (2020): Cities in the World: A new perspective on urbanization. https://www.oecd-ilibrary.org/sites/d0efcbda-en/index.html?itemId=/content/publication/d0efcbda-en. Accessed 05 May 2024
37. Moreno-Monroy, A.I., Schiavina, M., Veneri, P.: Metropolitan areas in the world. Delineation and population trends. J Urban Econ. **125**, 103242 (2021)
38. Guerra, Y.: Il ruolo delle città metropolitane alla luce della sentenza n. 240 del 2021: governance metropolitana e funzioni. Le Regioni **50**(3), 499–517 (2022)
39. Balletto, G., Mundula, L., Milesi, A., Ladu, M.: Cohesion policies in Italian metropolitan cities. Evaluation and challenges. In: Gervasi, O., et al. (eds.) ICCSA 2020. LNCS, vol. 12255, pp. 441–455. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-58820-5_33
40. Weckroth, M., Moisio, S.: Territorial cohesion of what and why? The challenge of spatial justice for EU's cohesion policy. Soc. Inclusion **8**(4), 183–193 (2020)
41. Lee, W.R. (ed.): European Demography and Economic Growth. Routledge, London (2021)
42. De Falco, S.: Are smart cities global cities? A European perspective. Eur Plan. Stud. **27**(4), 759–783 (2019)

National Spatial Data Infrastructure (NSDI) for Resilient Territorial Development: Building a National Disaster Risk Register (DRR) for Serbia

Ljiljana Živković(✉)

Republic Geodetic Authority, Belgrade, Serbia
liliana.zivkovic@gmail.com

Abstract. In recent decades the number and intensity of the natural and man-made hazards have been persistently increasing, continuing to undermine the efforts invested in achievement of the sustainable development. In order to prevent the new risk disasters, reduce the existing ones, and enhance territorial resilience by decreasing the exposure and vulnerability of the people, communities, economies and countries, UN has adopted in 2015 an action-oriented Sendai Framework for Disaster Risk Reduction for the effective disaster risk management, from global to local level. Due to then triggered needs for the various risk maps and, generally, for geospatial information for the Sendai Framework implementation, UN-GGIM has introduced in 2018 the Strategic Framework on Geospatial Information and Services for Disasters to lead the countries worldwide in production and distribution of the quality geospatial data and services, which are required for the timely decision-making and efficient coordination of operations in all phases of disaster risk management cycle. Among the other leads, one of the main guiding principles for implementing this strategic framework in any country directs to the National Spatial Data Infrastructure (NSDI), as a reliable platform for building a common database and infrastructure for quality and interoperable risk-related geospatial data and services. Since NSDI is usually administered by the national mapping agencies, the Republic Geodetic Authority has got a critical role in establishment of the national Disaster Risk Register and related infrastructure in Serbia for all national stakeholders' data gathering and analysis towards the common understanding of the disaster events. Despite there are more functionalities and elements yet to be developed in future, the current Disaster Risk Register and its infrastructure already confirm advantages of the multi-hazard and multisectoral approach to the disaster risk reduction and territorial resilience development.

Keywords: Disaster risk management (DRM) · national spatial data infrastructure (NSDI) · disaster risks register (DRR) · resilient territorial development · Serbia

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 172–188, 2024.
https://doi.org/10.1007/978-3-031-65238-7_12

1 Introduction

After the extraordinary rains and caused severe flooding in May 2014 in Serbia, which affected over 20% of the population and produced significant economic hardship, particularly for the poor and vulnerable, the Government of Serbia adopted the National Disaster Risk Management Program, aimed at establishing the comprehensive framework for the efficient and effective disaster risk management process. One of the key result of this program, which consists of the six components and is fully align with the UN Sendai Framework for Disaster Risk Reduction and UN-GGIM Strategic Framework on Geospatial Information and Services for Disasters, is a national Disaster Risk Register. This register is established as a subsystem of the existing National Spatial Data Infrastructure, and it uses the technical infrastructure and socio-technical framework developed and maintained today by the Republic Geodetic Authority, as national mapping agency for Serbia. Gathering geospatial data and information from the other national disaster risk stakeholders through the various standardized geospatial services, the main objectives of this register are to provide platform for the common risk understanding, to support risk-informed decision-making across all phases of DRM, as well as to introduce a disaster risk reduction and risk resilient territorial development within the land management and urban planning and development in general in Serbia. The last objective is of particular importance in the situation when urbanization is intensifying and climate changes aggravate the living and working conditions in every country, causing the effects spreading beyond the national borders and away from the location of disaster risk source.

Therefore, the aim of this paper is to present a state-of-the-art in building the national Disaster Risk Register for Serbia. Towards that end, after the Introduction the paper continues with the chapter that describes the current strategic frameworks and approach to the disaster risk reduction and resilience development, particularly focusing on the importance and role of the geospatial data and services for disaster risk management in the urban areas. After that, chapter Background provides information about the current situation in Serbia related to the geospatial data and services, i.e. NSDI, and the chapter with detailed description of the national Disaster Risk Register (context, concept, data and services). Paper provides then short Discussion explaining the advantages and disadvantages of developed solution, proposing the possible next steps in development of this register, before paper ends with the Conclusion chapter.

2 Geospatial Information and Services for Disaster Risk Reduction and Resilient Territorial Development

In recent decades the number and intensity of the natural and man-made hazards as well as the disaster losses due to these hazards have been persistently increasing, continuing to undermine the efforts for achieving the sustainable development, from global to local level. As a result, the previous disaster-preparedness approach has been replaced by the enhancing disaster-resilient approach to the territorial development process. This new approach assumes for new or future disaster risks to be prevented and for existing

ones to be reduced by tackling the disaster risk drivers[1] directly, decreasing thus the exposure and vulnerability to disaster of people, communities, economies and countries (Fig. 1). Exactly this proactive approach to the hazards and disaster risks has been supported worldwide since 2015 by the action-oriented Sendai Framework for Disaster Risk Reduction (Sendai Framework), which replaced the previous prevailingly the advocacy-oriented Hyogo Framework for Action (Hyogo Framework) for the disaster risk management [15, 20].

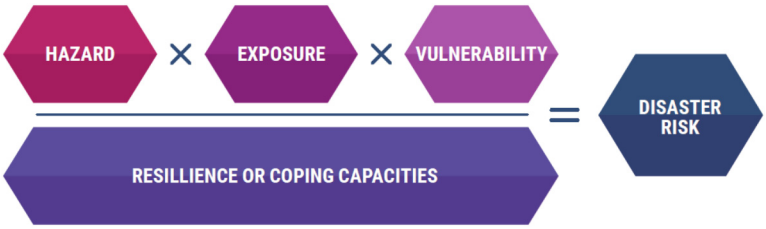


Fig. 1. Relationship between vulnerability, resilience and disaster risk, where higher is the exposure to hazard the higher is vulnerability and disaster risk, especially in absence or low resilience level: "…resilience can be seen as the opposite of vulnerability, as the ability of a system to withstand shocks and stresses, to bounce back better or recover from these…" [20]

In other words, comparing to the Hyogo Framework, Sendai Framework has identified for its four priorities areas the lists of concrete risk reduction actions on global, regional, national and local levels. Also, aimed at implementation of the integrated and inclusive measures[2] for establishing the multi-hazard and multisectoral disaster risk reduction practices in the countries, which would substantially reduce the disaster related losses while strengthening the overall territorial resilience, the Sendai Framework has identified the seven targets and thirteen guiding principles for this Framework appropriate implementation [14, 15].

Also, besides the fact that Sendai Framework covers more types of hazard comparing to the Hyogo Framework, including both those that are land-specific (like floods) and not spatially ubiquitous ones (like pandemics) [14, 18], the Sendai Framework' thirteen implementation guiding principles and listed four priorities' actions highlight –among the others- two factors or approaches significant for this framework successful implementation by each country. These approaches, which are in the focus of this paper, assume that [15]:

1. Effective disaster risk reduction process requires a multi-hazard and inclusive risk-informed decision-making approach based on the open exchange and dissemination of interoperable location-based or geospatial disaster risk information, like risk maps,

[1] Some of the key drivers of risk are: poverty and inequality, climate change, environmental degradation, climate change, unplanned urban expansion, poor land management/governance, weak institutional arrangements, limited implementation and enforcement capacity, lack of participation in decision-making [20].

[2] Including economic, structural, legal, social, health, cultural, educational, environmental, technological, political and institutional ones [15].

to decision makers, the general public and communities exposed to disaster risk(s), in an appropriate format by using the geospatial information technologies (like GIS) and related services [5, 9, 13, 15, 17, 18, 22]; and

2. Disaster risk reduction and management depends on the coordinating mechanisms and shared responsibilities between the different sectors and institutions on the national level, where the central Governments have critical enabling, guiding and coordinating role, but it is necessary to empower the local authorities and communities to reduce disaster risk. This is because the disaster risks have local and specific characteristics that must be understood for the right measures determination for disaster risk reduction (through decreasing the exposure and vulnerability to each hazard) [15, 18–20].

2.1 Geospatial Information and Services for Disaster Risk Reduction

In relation to the two described approaches above for the effective Sendai Framework implementation into the national disaster risk management (DRM) practice, UN-GGIM has introduced in 2018 the Strategic Framework on Geospatial Information and Services for Disasters (SF-GISD). The main aim of this framework is to lead efforts in making available and accessible the quality geospatial information and services necessary for the timely decision-making and efficient coordination of operations through the national DRM cycle, from prevention and preparedness to response and recovery from the disasters (Fig. 2). However, besides supporting countries in the implementation of Sendai Framework priorities, this strategic framework also supports the achievement of 2030 Agenda for Sustainable Development, i.e. Sustainable Development Goals (SDGs), as well as the Paris Agreement on Climate Change, as shown on Fig. 3 [17, 20, 23].

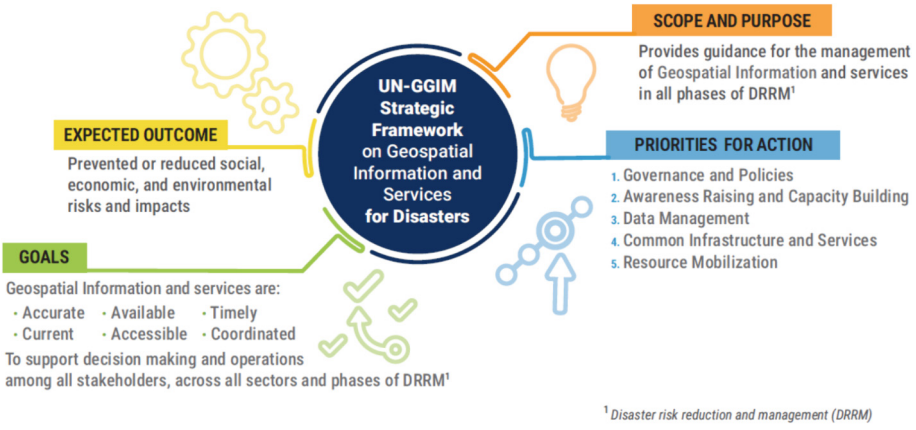


Fig. 2. Overview of the UN Strategic Framework on Geospatial Information and Services for Disasters [23]

In light of the Sendai Framework, the outcome of SF-GISD implementation assumes that "human, socioeconomic and environmental risks and impacts of disasters are prevented or reduced through the use of geospatial information and services". Similar to

the Sendai Framework, the SF-GISD outcome and goals implementation are supported by the concrete list of actions for global, regional, national and local levels for all five priorities, including the five major principles for guiding the SF-GISD implementation. Among those five, one guiding principle that is particularly important for the aim and topic of this article stresses that "implementation of the [SF-GISD] framework shall comply with the standards and requirements of the NSDI" [17].

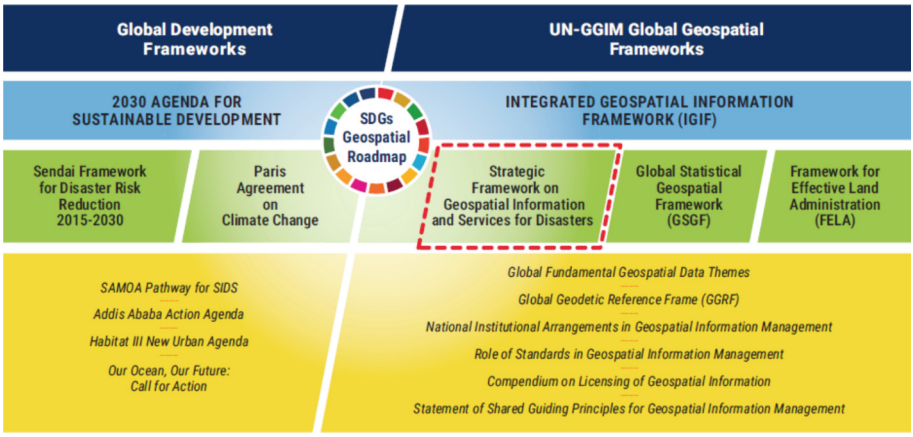


Fig. 3. UN-SFGISD within Global Development and UNGGIM Frameworks [23]

Since NSDI is confirmed as a one of the pillars for production and distribution of the quality and interoperable geospatial information and services provision for the national DRM framework, the national mapping agencies that are usually responsible for the NSDI initiatives have been recognised as one of the leading stakeholders for SF-GISD implementation, along the national statistical institutions, national disaster management agencies, etc. [17]. This is due to the fact that national mapping agencies by applying the relevant international and/or national standards for the geospatial data and services, like INSPIRE Directive in Europe, have already developed or are developing infrastructure and capacities needed for the DRM process, and could thus support efficiently "a common and accessible database system of minimum/baseline geospatial information and services requirements, including an initial list of essential elements of information addressing all phases of DRM" [17]. Besides the other elements, this database system includes both common and fundamental operational datasets, like administrative boundaries, critical infrastructures and earth observation data. These data are already administrated by the national mapping agencies and posses required accuracy, resolution, authoritativeness, integrity, openness and interoperability imposed by the relevant national regulation [6, 12, 17].

Finally, the implementation of shared, quality and interoperable geospatial data and information using the geospatial technologies for the disaster risk management is not a new idea or endeavour [13], but the systematised approach proposed by the Sendai Framework and SF-GISD for the natural and man-made disasters prevention, preparedness, response and recovery make it possible to compare the national DRM frameworks

(Fig. 4) and create best practices in usage of the geospatial information and technologies for enhancing the territorial disaster risk resilience. [5, 9, 12].

S. No.	Translated Products and Services	Activity	Criteria
1	• Base maps (topographic maps, geological data, land-use map, Elevation data) satellite images, LIDAR or Photogrammetric • Disaster risk maps (simulation, prediction) and assessment templates (regulation, procedure for reaction), (maps, documents)	Collection and processing, quality and accuracy ▪ Geospatial Data ▪ Statistical Data	1. Existing data
2	• Situational awareness (maps, systems) • Real-time services (alert messages, prediction maps) • Post-Disaster Need Assessment- procedural regulations; (documents) • Disaster assessment regulations. Data (documents) Application software; Assessment (software) • Disaster losses-Disaster loss registers; (map, documents)	Collection of real-time data, forecasting, early warning, disaster assessment	2. Real-time data
3	• Database management systems (software) SDI and Platforms (software/services) • Standards (documents)	Data management, sharing and dissemination	3. Data management
4	Traditional, local or scientific knowledge (document) • Public Education, Awareness and Knowledge Strategies (document)	Capacity building and public participation	4. Capacity building
5	• Policy to maintain data, services and systems (documents)	Resource mobilisation	5. Resources mobilisation

Fig. 4. Criteria for comparing the national DRM systems implementation in line with Sendai Framework and SF-GISD [12]

2.2 Towards Resilient Territorial Development

In order to build awareness, promote a culture of disaster prevention and resilience, support mutual learning and sharing experiences, etc., the Sendai Framework implementation at the local level is relying –among the other actions- on the "Making Cities Resilient: My City is Getting Ready" (MCR2030) campaign, launched first back in 2010 [15, 20, 21].

This focus on the disaster risk reduction in the cities is result of the significance of urbanisation process today globally, including the need for climate change adaptation, which calls for the Sendai Framework's actions to particularly target the disaster risk drivers in the urban areas through strengthening existing land use and urban planning practices, especially in developing countries [19, 20].

Urban land use planning is seen both as a key actor for preventive measures, but also an important instrument for the disaster recovery phase, as proposed by the Sendai Framework's Priority 4 [15, 18, 19, 24]. In other words, urban planning has an important role in the reducing current and preventing future disaster risks since 60 per cent of all areas that will be urban in 2030 are yet to be built [20]. There is hence an enormous opportunity or challenge for the planning to both support future urban growth and retrofit the existing urban areas to be more resilient to shocks and stresses in future.

However, current integration of DRM process in the urban planning practices is often limited [19, 20]. According to the results of MCR2030 report for 2019 about the

progress of local governments in reducing disaster risk, significant efforts still need to be made for reducing disaster risks in the cities and achieve urban resilience and SDGs, in all categories including the Technology one[3] [21] that is important for the SF-GISD actions implementation for the right land use and investment decision-making, which is also in the focus of this paper.

3 Background

After the extraordinary rains and following severe flooding in May 2014, which affected more than 22% of the Serbian population and caused significant economic hardship, particularly for the poor and vulnerable, Serbia adopted the National Disaster Risk Management Program (National Program) [7]. The objective of the National Program is to support the Government of Serbia in establishing a comprehensive framework for the DRM process, able to support it (Government of Serbia) in coordination, distribution and implementation of the funds and activities relevant for reducing the existing disaster risks and preventing future ones, as well as enhancing overall territorial resilience to disaster risks in Serbia [7]. In order to stimulate the effective risk reduction and efficient response to the natural and man-made disaster risks, the National Program guiding framework is divided into the six components[4] with a list of eligible activities for investment for each of them (components) in the coming years.

Relying on the non-structural risk measures of the National Program's Component 3, as well as on established legal framework for the DRM on national level [1–3], which are fully aligned with the Sendai Framework, Serbia has began establishment of the national Disaster Risk Register (DRR) [4] and related information infrastructure, aimed to implement actions proposed under the SF-GISD's Priority 3: Data management and Priority 4: Common Infrastructure and Services.

This register development is the legal responsibility of the Ministry of Interior Affairs' Sector for Emergency Management, while all the other relevant institutions and authorities are obliged to provide updated authoritative data from their responsibilities relevant for the DRM process. Due to the developed technical capacities, the Republic Geodetic Authority (RGA) that is responsible for the INSPIRE Directive implementation in Serbia and NSDI management, is responsible also for provision and maintenance of the technical infrastructure for the DRR in according with the exiting geospatial regulations [2, 3].

This means that national DRR in Serbia is established and maintained as a subsystem of the Serbian NSDI, as prescribed by the RGA Strategic Action Plan for the NSDI, relied on the UN-IGIF guidelines [8]. In the same strategic document, the establishment of DRR is also linked with the other NSDI improvements that would in future secure

[3] Like Develop and update hazard maps (category: Policy and Plans), Establish information system on hazards and set up a mechanism to update; Enhance intuitional capacity, training program for concerned personnel, technology and equipment support (Spatial mapping and GIS); etc. (category: Technology).

[4] Component 1–6: Institutional building; Disaster risk identification and monitoring; Structural and nonstructural risk reduction; Early warning systems and preparedness; Risk financing strategies; Resilient recovery.

the quality geospatial data and services needed for the DRM process in Serbia in line with the SF-GISD, including the collection and recording of the disaster loss data for the Sendai Framework's DesInventar database.

Finally, as a result of performed activities on the Sendai Framework implementation on the local level, nine Serbian local self-governments participated in the MCR2030 campaign and analysis of the disaster resilience scorecards [11]. Measurements of the "Ten Essential for Making City Resilient" showed relatively good and similar results or lacks in all nine local self-governments, with conclusion that disaster risks information –namely, the risk maps- available on the NSDI platform GeoSerbia via DRR are not yet incorporated in the urban planning documents preparation, like the obligatory General Urban Plan, in order for a sustainable urban and territorial development to be accomplished.

4 Disaster Risk Register

According to the guiding principles and priorities for the SF-GISD implementation, geospatial information and services for the DRM should comply with the standards and requirements of the existing NSDIs, while national mapping agencies that play a key role in their implementation and development should be fully supported (financially and in other ways) towards the better availability and accessibility of quality geospatial information and services for all phases of DRM [17].

Towards this end, establishment of a modern central register for the disaster reduction in Serbia is supported at the moment by the two EU-funded projects, namely "EU for Civil Protection and Disaster Risk Resilience Strengthening in the Republic of Serbia" [10] and "EU for enabling a more responsive healthcare system" [25], where the RGA has an important role to build a national DRR and provide the modern common infrastructure and services necessary for the DRM process flow [17].

Establishment of the DRR within the Serbian NSDI, aligned with the EU INSPIRE Directive and the EU Initiative to Enhance Data Interoperability [10, 22], has begun in 2020. Once established, DRR has been connected also with the existing national Disaster Risk Information System, where this system uses the data from DRR for its own purposes and vice versa.

After the public launching of DRR in 2022, this interactive, electronic, geographic information database for the territory of Serbia, which contains geospatial data and services important for the risk management domain [4], is now under further development and upgrading with the public health related risks data that would with the other risks information (floods, landslides, earthquakes, etc.) lead to better risk-informed decision-making and overall risk reduction and emergency preparedness in Serbia in future [25].

4.1 DRR Concept

In sense of its context, DRR is planned and implemented as the subsystem of Serbian NSDI and its digital platform GeoSerbia, meaning that it is loosely integrated with its other subsystems from which it gathers thematically relevant data, provides analytical capacities for generations of risk-relevant data products, and distributes them to the

identified data users systematically. This means that DRR is intended primarily to tackle the identified challenges related to the data sharing among the various stakeholders on national and local level in Serbia. In relation to this, it is planned for the DRR to eventually include several functionalities, which are in line with the Sendai Framework and SF-GISD, as presented below on the Fig. 5.

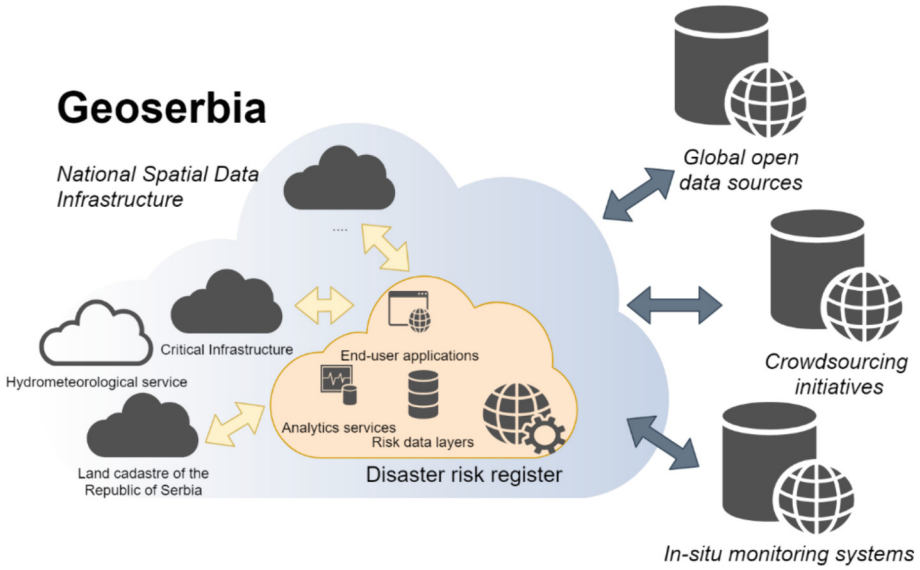


Fig. 5. The context of DRR requires support for different functionalities, like data harvesting from third party data sources, integration of sensory platforms in support of disaster risk management, support to crowdsourcing platforms for rapid data collections, support to development of dedicated applications for DRM, etc. [16]

In accordance with its purpose, DRR is defined as one-stop-shop for all risk-relevant data and services that includes four conceptual layers, as outlined on the Fig. 6.

4.2 DRR Data

Serbian NSDI and its digital platform GeoSerbia [26, 27] contains today more than 280 various datasets from the different national stakeholders, including both main (infrastructure, cadastre, topography, statistics) and specific data categories (natural resources, seismology, condominium register, agriculture, forestry, land cover, government and public institutions, geology, economy, real-estate market price register, etc.). This broad basis of available geospatial datasets and registers (Fig. 7) has provided the necessary information for performing the territorial vulnerability analysis and assessment and establishment of the DRR content, making it now one of the strategic subsystems within the Serbian NSDI.

Besides the existing NSDI geospatial datasets and registers, DRR includes relevant risk-related data and information. Some of these have been already created with the

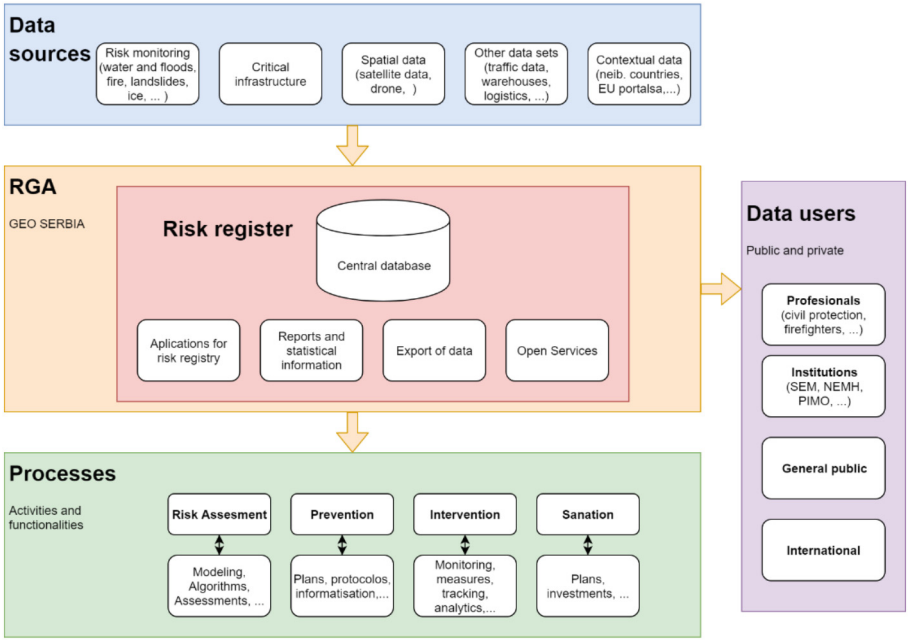


Fig. 6. The DRR concept includes four conceptual layers: 1) NSDI digital platform GeoSerbia with DRR and other subsystems; 2) data sources layer; 3) processes layer; and 4) risk data users layer [16]

location information by the relevant national stakeholders and, then, integrated in DRR and its Web GIS platform via appropriate Web services; on the other hand, some of the risk-related data and information were created for the first time during the establishment of DRR, by linking the non-geospatial datasets with the existing geospatial datasets (consisting of appropriate entities with a location information), or produced as results of the risk analysis or assessment before their integration with the other DRR geospatial datasets (Fig. 8).

4.3 DRR Services

In Serbia, established DRR is the primary source of all relevant information at national level related to the disaster risk assessment, prevention or reduction, intervention, and recovery and reconstruction. This means that implemented DRR solution provides the crucial geospatial services required by the decision-makers, which could be used to support various aspects and all phases of DRM cycle in any part of Serbia, including decisions on actions before disasters, during disasters and after disasters.

Therefore, in line with the SF-GISD recommendations for geospatial services for disaster, DRR system in Serbia encompasses the widely recognized standard geospatial services for managing data and information needed to all key stakeholders, to have a common picture of the disaster events and make decisions in all phases of the DRM. However, due to the sensitivity of DRM geospatial data and information as well as

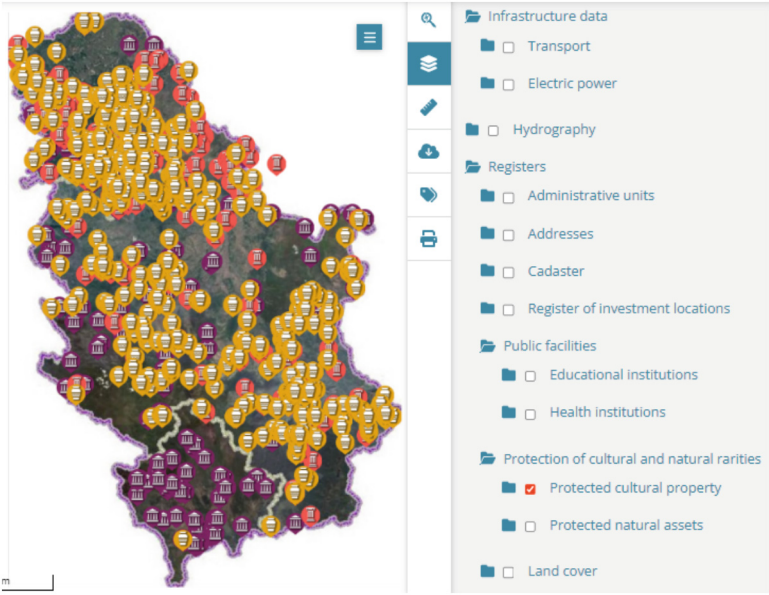


Fig. 7. NSDI datasets and registers integrated and provided through the DRR Web GIS: Administrative unit register, Address register, Cadastral parcels, Digital ortophoto and satellite images, Land cover, Geographical names, Protected cultural assets (presented here), etc.

prescribed data management policies related to the security and control for accessing and using the same, provided OGC Web services for DRR geospatial data and information are accessible at the moment only to registered users, i.e. the key DRM stakeholders. For these users, DRR platform functionalities are offered via the standard geospatial data exchange services (WFS, WMS, WPS) and REST APIs built in a service layer of the DRR system (Fig. 9), through a single access point on the DRR portal, including web applications offered therein.

Besides these geospatial services, through the DRR platform users could access the Web services available at the NSDI digital platform GeoSerbia, as well as those available through the RGA Metadata catalogue. In both cases, it's about the geospatial services that are developed in accordance with the OGC standards (WFS, WMS, etc.) for the available INSPIRE-compliant RGA's geospatial datasets and registers. Finally, all DRR Web GIS users could add the WMS service from the cloud in order to integrate in the common environment geospatial data or information needed for the risk-related decision-making.

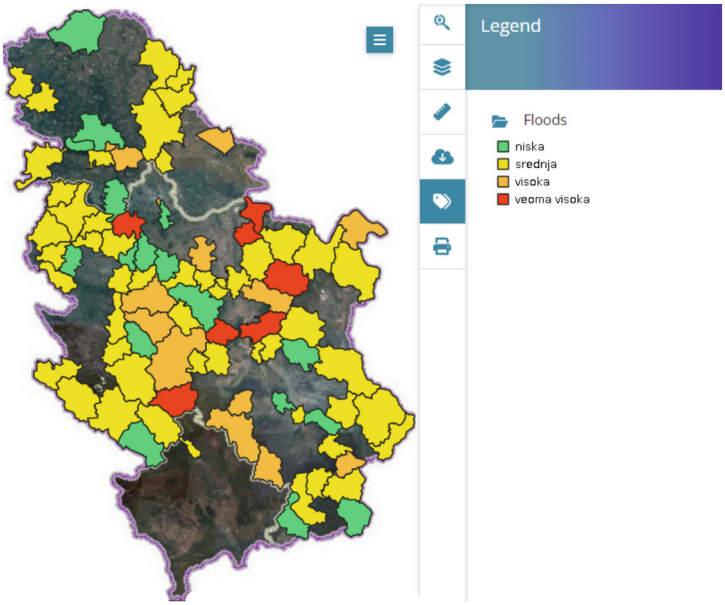


Fig. 8. Risk-related datasets in the DRR Web GIS environment include data and information on the main risk hazards identified as relevant for the territory of Serbia, like flood risks (presented here on the municipality level), forest fire risks, extreme weather phenomena, seismic risks, landslide risks, technological risks and risks of different epidemic diseases

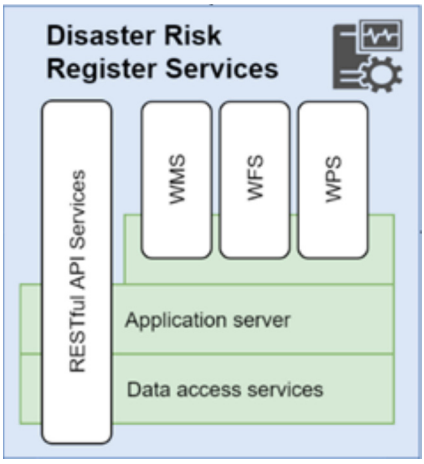


Fig. 9. Service-layer of DRR [16]

5 Discussion: DRR and Its Application for Territorial Resilience

As described in the previous chapter, DRR solution implemented in Serbia for the DRM process steering on national level is relying and uses advantages of the already developed NSDI infrastructure and its socio-technical framework developed by the RGA and other stakeholders. Thus, DRR establishment is a result of the close collaboration between the RGA and other relevant national key stakeholders, exclusively from the public sector for time being, who succeeded to set up this common and accessible database system for the DRM on national level in a relatively short time. Taking into account the identified main hazards relevant to the territory of Serbia, here presented DRR system has today only the baseline geospatial information and services needed for the DRM process flow. Also, the geospatial data and information integrated within existing DRR possess needed accuracy, resolution, authoritativeness, integrity and interoperability for national level risk-informed decision-making and risk management, but still more efforts have to be invested by the key stakeholders to improve these risk-relevant data and information quality as well as openness required for building the similar systems for the risk reduction and resilient territorial development on regional and, particularly, local or urban area level, following the MCR2030 initiative (Fig. 10). In other words, besides continual development and maintenance and technological improvement of the established DRR for national level, a more should be done on the promotion and education about benefits of this system for a sustainable regional development and urban land use planning and implementation monitoring, which needs better risk understanding and various risk maps with the higher precision producing for the right decision-making.

Overall, the established DRR provides the basic risk assessment maps and other reference information that are crucial inputs for both national and local DRM plans preparation, but also important inputs for the formulation and elaboration of different projects, programs and activities, including spatial and urban plans for resilient territorial development. Also, it's important that developed DRR system has put forward and prescribed the necessary common standards, protocols and processes for the DRM domain in Serbia, which makes it a model for building the similar systems/SDIs for the other domains in Serbia, from national to local level. These common geospatial standards are particularly important for creating the common picture of disaster events by all key stakeholders, national and international, since current intensive urbanization and rapid climate changes' negative impacts have no boundaries and make sustainable development goals even more challenging for achievement.

On the disadvantage side, established DRR still lacks population data, including the other statistics needed for the optimal DRM planning and plans implementation, monitoring and evaluation, which are of the key importance for the risk reduction and territorial resilience enhancement, particularly in urban areas. Also, connections to the risk-relevant regional and international databases are still to be established, while the integration of sensory networks for real-time data is left to be implemented in the coming years as well.

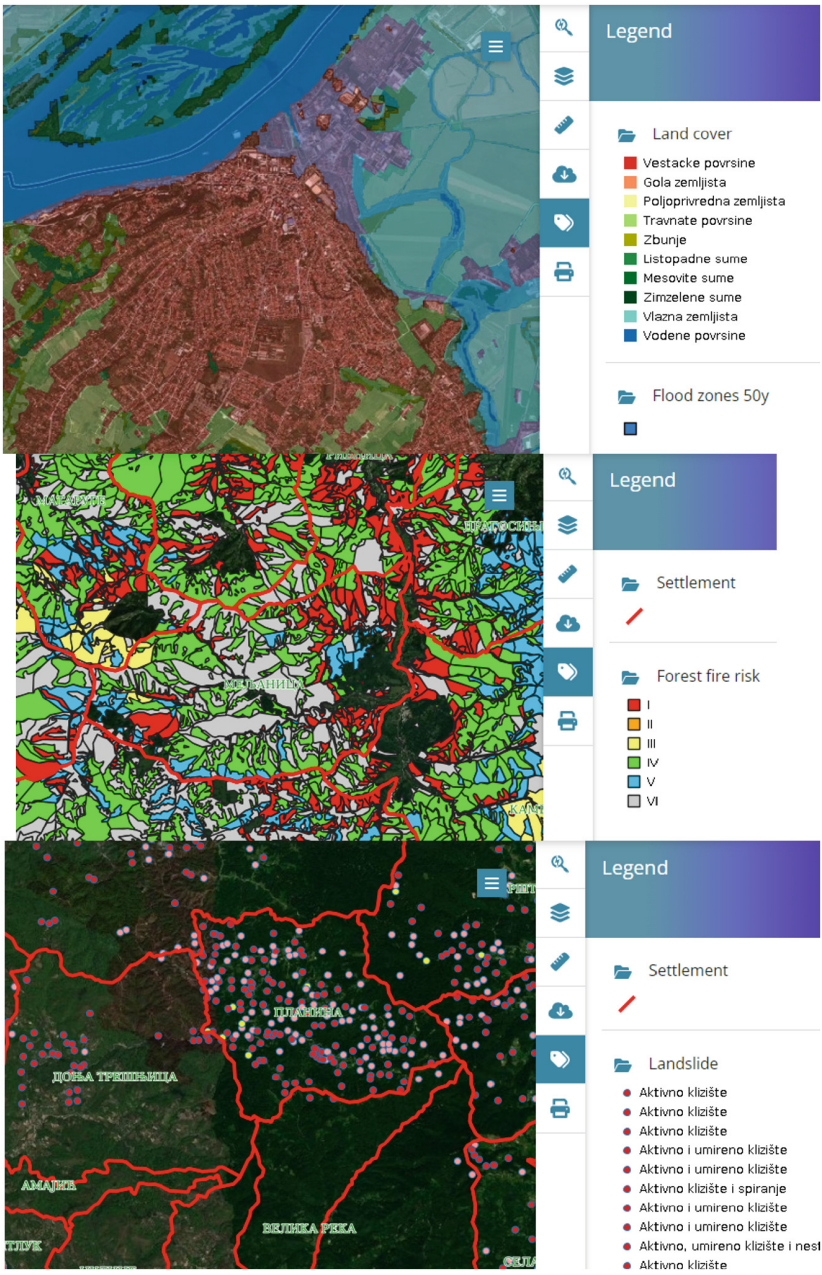


Fig. 10. Rapid urbanization and dynamic climate changes in Serbia need risk data and information with the higher precision on local and regional level for preventing the new risks, reducing existing ones and making the cities and regions resilient in future. National DRR data examples: land cover data combined with flood risk data for 50-year return with different resolution (up); forest fires risk map created on regional level (middle); landslides location on settlement level (down)

6 Conclusions

In order to foster the consistent response and effective solutions for reduction and management of the negative effects caused by the natural and man-made hazards worldwide, which persistently undermine the efforts invested in achievement of the sustainable development, UN has adopted in 2015 the Sendai Framework for the effective DRM process establishment on all levels. Aiming to support implementation of this strategic framework with recognized advantages of the location information, UN-GGIM has adopted 3 years later the SF-GISD that –among the other guidelines- directed to the NSDI as the proper national geospatial framework for producing and distributing the quality geospatial data and information for all phases of DRM process.

On one side, developed as the subsystem of the NSDI in Serbia, the national DRR is today the main source of quality and interoperable geospatial information for building the common understanding and decision-making about the disaster events among the multisectoral stakeholders community. On the other side, this national geospatial framework combined with the different risk information presents the reliable DRM platform for implementing the right measures for preventing the new/future risk disasters, reducing the existing ones, and enhancing territorial resilience both for urban and regional areas.

Thus, based on the INSPIRE-compliant NSDI datasets and Web services, DRR provides through the established Web GIS platform the basic risk assessment maps and other reference information that are crucial inputs for the DRM plans preparation, but also important inputs for the preparation of other strategic documents in Serbia, like spatial and urban plans.

However, besides the already developed advantages and functionalities that make DRR the one-stop-shop for all risk-relevant data and services in Serbia today on national level, there are needs and plans for future development that will enhance this national register applicability for the effective DRM process especially on the local level.

References

1. Official Gazette of the Republic of Serbia (2018). Law on disaster risk reduction and emergency management. https://www.pravno-informacioni-sistem.rs/SlGlasnikPortal/eli/rep/sgrs/skupstina/zakon/2018/87/1/reg
2. Official Gazette of the Republic of Serbia. Rulebook on the content, manner of establishing and maintaining the Disaster Risk Register (2019). https://www.pravno-informacioni-sistem.rs/SlGlasnikPortal/eli/rep/sgrs/ministarstva/pravilnik/2019/78/8
3. Official Gazette of the Republic of Serbia. Regulation on the obligations of the subjects of the Disaster Risk Reduction and Emergency Management system in the process of creating the Disaster Risk Register (2020). http://www.pravno-informacioni-sistem.rs/SlGlasnikPortal/eli/rep/sgrs/vlada/uredba/2020/122/2
4. Disaster Risk Register (DRR). https://drr.geosrbija.rs/drr/home
5. Smaldone, R., Attolico, A., Scorza, F.: Enhancing territorial and community resilience through a structured institutional governance: the resilience HUB of the province of Potenza. In: Gervasi, O., et al. (eds.) ICCSA 2023. LNCS, vol. 14110, pp. 25–39. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-37123-3_3

6. Živković, L.: Project smart SDI: concept for improving NSDI for sustainable development in Serbia. In: Gervasi, O., et al. (eds.) ICCSA 2023. LNCS, vol. 14105, pp. 549–560. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-37108-0_35
7. World Bank Group. Serbian - National Disaster Risk Management Program: Concept Note (English). Washington, D.C. (2021). http://documents.worldbank.org/curated/en/863191614943769186/Serbian-National-Disaster-Risk-Management-Program-Concept-Note
8. Republic Geodetic Authority. Strategic action plan for the national spatial data infrastructure of the Republic of Serbia (2021). https://en.rgz.gov.rs/content/pages/english/Structure/NSDI%20Strategic%20Actions%20Plan-4.pdf
9. Migliorini, M., et al.: Data interoperability for disaster risk reduction in Europe. Disaster Prev. Manag. **28**(6), 804–816 (2019). https://doi.org/10.1108/DPM-09-2019-0291
10. United Nations Development Programme. EU for Civil Protection and Disaster Risk Resilience Strengthening in the Republic of Serbia (2020). https://www.undp.org/sites/g/files/zskgke326/files/2022-09/undp-rs-DRR-ProDoC-Amendement-ENG-2020.doc.pdf
11. UNDRR. Serbia Report outlining the levels of urban resilience in the Republic of Serbia's cities and municipalities within the MCR2030 initiative 2021–22, United Nation Office for Disaster Risk Reduction (UNDRR) (2023). https://www.undrr.org/media/81295/download?startDownload=true
12. Ghawana, T., Pashova, L., Zlatanova, S.: Geospatial data utilisation in national disaster management frameworks and the priorities of multilateral disaster management frameworks: case studies of India and Bulgaria. ISPRS Int. J. Geo Inf. **10**(9), 610 (2021). https://doi.org/10.3390/ijgi10090610
13. Giuliani, G., Peduzzi, P.: The PREVIEW Global Risk Data Platform: a geoportal to serve and share global data on risk to natural hazards. Nat. Hazards Earth Syst. Sci. **11**, 53–66 (2011). https://doi.org/10.5194/nhess-11-53-2011
14. Aitsi-Selmi, A., Egawa, S., Sasaki, H., et al.: The sendai framework for disaster risk reduction: renewing the global commitment to People's Resilience, Health, and Well-being. Int. J. Disaster. Risk Sci. **6**, 164–176 (2015). https://doi.org/10.1007/s13753-015-0050-9
15. UN. Sendai Framework for Disaster Risk Reduction 2015–2030 (2015). https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030
16. RGA. Business and technical architecture of the disaster risk register of the Republic of Serbia (internal documents) (2020)
17. UNGGIM. UN Strategic Framework on Geospatial Information and Services for Disasters (2017). https://ggim.un.org/documents/UN-GGIM_Strategic_Framework_Disasters_final.pdf
18. Greiving, S., Kruse, P., Othmer, F., Fleischhauer, M., Fuchs, M.: Implementation of risk-based approaches in urban land use planning—the example of the City of Erftstadt, German. Sustainability **2023**(15), 15340 (2023). https://doi.org/10.3390/su152115340
19. King, D., Gurtner, Y., Firdaus, A., Harwood, S., Cottrell, A.: Land use planning for disaster risk reduction and climate change adaptation: operationalizing policy and legislation at local levels. Int. J. Disaster Resilien. Built Environ. **7**(2), 158–172 (2016). https://doi.org/10.1108/IJDRBE-03-2015-0009
20. UNDRR. Words into Action - Implementation guide for land use and urban planning (2019). https://www.undrr.org/sites/default/files/2022-12/67430_landuseandurbanplanningforpublicrev.pdf
21. UNDRR. Making Cities Resilient Report 2019: A snapshot of how local governments progress in reducing disaster risks in alignment with the Sendai Framework for Disaster Risk Reduction (2019). https://www.undrr.org/publication/making-cities-resilient-report-2019-snapshot-how-local-governments-progress-reducing

22. EC New European Interoperability Framework Promoting seamless services and data flows for European public administrations. https://ec.europa.eu/isa2/sites/default/files/eif_brochure_final.pdf
23. UNGGIM. UN Strategic Framework on Geospatial Information and Services for Disasters – Annex 1 (2022). https://ggim.un.org/documents/GGIM-Framework-Disasters_Annex1%20.pdf
24. UN: New Urban Agenda (2017). https://habitat3.org/wp-content/uploads/NUA-English.pdf
25. United Nations Development Programme and World Health Organization. EU for enabling a more responsive healthcare system (2023). https://responzivnije-zdravstvo.euzatebe.rs/en/about-project
26. NSDI website: https://geosrbija.rs/geosrbija-wp/
27. Digital geospatial platform Geosrbija: https://a3.geosrbija.rs/

Serious Digital Geogames and Their Implementations Enhanced by Artificial Intelligence, Mixed- and Augmented-Reality

Alenka Poplin(✉)

Iowa State University, Ames, IA, USA
apoplin@iastate.edu

Abstract. This paper concentrates on technological advancements of serious digital geogames. Geogames are games that are placed in a spatial context and often aim at realistic visualization of real-world situations. Novel technologies such as mixed-reality and augmented-reality represent opportunities for more advanced geogame design. Artificial intelligence (AI) tools can expand geogame concepts implemented with technologies that aim to immerse users into the game world. This paper overviews virtualized geometry, procedural content generation, and biometric feedback as novel AI expansion. Virtualized geometry can contribute to a more realistic visualization of geogame environments. Procedural content generation may automatically generate new content, game levels, characters, and unpredictable events to increase conflict in geogames that can make them more appealing to the players. Biometric feedback may be used to model the game based on the state and condition of the player. This paper summarizes the potential for expansion of serious digital geogames and discusses the opportunities AI offers as a novel contribution to this field.

Keywords: serious geogames · mixed- and augmented-reality · artificial intelligence · procedural content generation

1 Introduction

Serious games are games that are developed for more than just fun (Abt 1970, Ritter-feld, Cody and Vorderer 2009). They concentrate on solving real-world problems, dealing with real-world situations, and may provide learning and training opportunities. Geogames are a novel research area with a focus on games that include spatial component; geo originating from an ancient Greek word gaia meaning "and" or "earth". Research on geogames goes back to the first papers published in 2005 and 2006 by Schlieder and his group at the University of Barmbek in Germany (Schlieder et al. 2005, Schlieder et al. 2006). At that time, a geogame was defined as a location-based game that makes use of positioning technology (e.g. GPS) and integrates the player's position into the logic of a game. A few years later, Ahlqvist and his collaborators (Ahlqvist et al. 2012) expanded this definition of geogames to mean "all games that use real-world spatial information and are mediated by geographic information technology (GIS)". A fundamental idea

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 189–201, 2024.
https://doi.org/10.1007/978-3-031-65238-7_13

underlying the approach taken by geogames is their focus on creating an online world that mirrors authentic real-world geography. This world may be realized by a full range of GIS supported mapping and processing services. Since these beginnings of geogames, the idea has been expanded into many fields of study, from implementations and development in urban planning (Poplin 2012, 2014), geography (de Sena et al. 2021) and cultural heritage (de Andrade et al. 2020), to mention just a few. Geogames can also be non-digital board games. The most recent edited book by Randal and Lasansky (2023) introduces a collection of articles and essays about place and space as the central element of the selected games and their specific take on the representation of place, architecture, urbanism, planning, history, heritage conservation and landscape history.

This article investigates the future of geogames, research of this specific area and the impact artificial intelligence (AI) developments may have on implementation of digital serious geogames. It attempts to answer the following questions: "What elements of AI can be the most beneficial for further development of serious digital geogames? How can mixed- and augmented-reality contribute to the enhancement of these games?" The term "game AI" is used to refer to a broad set of algorithms that also include techniques from control theory, robotics, computer graphics, computer science and agent-based modeling (Yannakakis et al. 2014, Togelius 2018). This article summarizes developments and advances that may expand and inspire further development of geogames and geoinformation science in general. Specifically virtualized geometry, procedural content generation, modeling player's behavior based on biometric feedback, and implementations of mixed- and augmented-reality are selected as potentially the most influential developments for the field of geogames. The article concludes with a discussion and further research directions.

2 Serious Digital Geogames and Their Implementations

2.1 Research on Serious Digital Geogames

Research on digital geogames is novel and its beginnings go back to the initial publications by Schlieder and his colleagues (Schlieder et al. 2005; Schlieder et al. 2006). These publications introduced the term geogame which was at the time defined as a location-based game (LBG) that is played outside in the environment with the help of mobile devices. Their research is followed by publications in urban planning and community engagement emerging, first at the Hafen City University Hamburg in Germany and later at Iowa State University (Krek 2008, Ben Hiba et al. 2009), University of Hasselt in Belgium (Devisch 2008), and Emerson College in the US (Gordon and Manosevitch 2010). At that time, these three hubs focused on the implementation and use of games in urban planning and community engagement as part of the planning for the future of neighborhoods in cities. The next breakthrough of the research on geogames can be marked with the publication by Ahlqvist and his colleagues (Ahlqvist et al. 2012). Their research is influential because of their expansion of the definition of geo- games and their test implementation and integration with a geographic information system (GIS) technology. They defined geogames to be "all games that use real-world spatial information and are mediated by geographic information technology (GIS)".

Researchers at the Federal University of Minas Gerais in Belo Horizonte, Brazil, joined the research on geogames, contributing with two PhD studies: the first one by de Andrade (2019) with the focus on cultural values in the village called Tirol in Brazil and the second one by de Sena (de Sena et al. 2021) who developed the game GeoMinasCraft which enabled players to explore mining areas of Ouro Preto in Brazil and learn about biodiversity. The next key milestone was the first edited book titled *Geo-games and Geoplay: Game-based Approaches to the Analysis of Geo-Information* published in 2018 and edited by Ahlqvist and Schlieder (2018). This book shows study cases of developed and implemented games as well as projects researchers were working on at that time. In 2020, Poplin and Schwartz (2020) edited the first journal published online titled *Gaming and Geoinformation* which features nine articles with a focus on games and geospatial information. Research in this field continues and offers value in a variety of application areas.

2.2 Application Areas of Serious Digital Geogames

Serious digital geogames application areas may include urban planning and community engagement, cultural heritage, geography, climate change, geodesign, architecture, disaster management, and well-being, to mention just a few.

Urban Planning and Community Engagement. Most of the literature on serious digital geogames concentrates on envisioning, designing, implementing and testing games that can be used in urban planning (Devisch 2008, Krek 2008, Poplin et al. 2017). These geogames can be implemented in various stages of the planning process, engaging residents to discuss visions and further developments of the cities and their neighborhoods (Gordon and Manosevitch 2010, Gordon et al. 2011, Gordon and Schirra 2012, Poplin 2011, 2012, 2014), contemplate proposed changes (Devisch at al. 2016), used as pop-up moving planning or playful gamified city engagement festivals (Poplin et al. 2023b), or implemented in a digital way as part of an online cloud-based participatory platform (Poplin 2022). Some of these games concentrate on a specific group, often on kids and ways to engage them to envision the future of places in which they live (Poplin et al. 2020b, de Andrade and de Sena 2020a, Poplin et al. 2023a).

Cultural Heritage. Preserving and understanding cultural heritage is another application area for geogames. Researchers such as de Andrade and Foroughi together with their collaborators explore how can geogames be utilized to study cultural values, explore them, and raise the awareness of their preservation (de Andrade et al. 2016, Foroughi et al. 2023).

Geography. Geo-diversity and learning about it in a particular geographic area is the goal of the geogame GeoMinasCraft developed by de Sena et al. (2021). Enabling players to explore characteristics of landscapes, their specifics, and qualities by enabling game non-playable characters (NPCs) to have an active role in the game while the player can communicate with them, ask questions, move through game landscapes and learn about the geographic areas. Such games may provide players with a new understanding of these landscapes and empower them with a deeper understanding of their role in creating livable environments for the residents.

Climate change and its consequences can be visualized in the form of scenarios or what-if futures enabled by geogame environments. Geogames offer creative possibilities to play with scenarios and visions for the future under specific conditions, explore their impacts and effects, and study possible consequences of climate change on people and environment (de Andrade 2019, 2020).

Geodesign is the process of designing for the future with the help of geospatial data (Steinitz 2012). Geogames can enhance this process with their playful ability to visualize the content discussed and engage residents in a playful way (de Andrade 2019, de Sena et al. 2021).

Architecture. Geogames can be implemented in architecture to display and study conditions of buildings, energy consumption, or even decision-making of the inhabitants and the choices they make regarding the upkeep of their buildings and homes or their efforts to reduce energy consumption (Poplin 2020, de Andrade et al. 2024).

Disaster Management and Well-Being. Geogames may serve as simulation tools presenting scenarios of evacuation, possible ways of reacting in emergency situations, or as a teaching tool for the rescue teams, medical personal or residents in a drill setting (Tomaszewski et al. 2018, 2020, Schwartz and Tomaszewski 2021).

3 Mixed-Reality Serious Digital Geogames

3.1 Mixed-Reality (MR)

Researchers of modern serious digital geogames may want to explore the use of mixed-reality. Mixed-reality (MR) encompasses all possible variations of the mixture between reality and virtuality in a composition of real and virtual objects and characters. It consists of both augmented-reality where the virtual augments the real, and augmented-virtuality, where the real augments the virtual. The physical and the digital worlds are blended and mixed. Digital imaginary elements and objects can interact with physical elements. The term mixed-reality (MR) was first introduced in a 1994 paper by Paul Milgram and Fumio Kishino titled *A Taxonomy of Mixed Reality Visual Displays* and is visualized in Fig. 1.

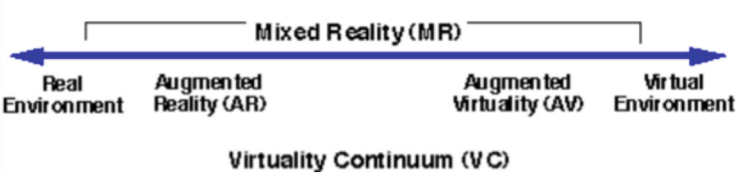


Fig. 1. Defining mixed reality by Milgram and Kishino (1994)

MR experience can be enabled by wearable mixed-reality devices such as MR glasses, cameras and sensors that place 3D digital objects in the real world. These digital objects appear as projected holographic images. The user can then interact with these

objects, move, and alter them. This effect is accomplished with the help of cameras, sensors, and AI technologies. It may also incorporate geographical mapping, hand tracking or vocal input. Implementation of MR systems may involve signal processing, computer vision, computer graphics, user interfaces, human factors, wearable computing, mobile computing, information visualization, or the design of displays.

3.2 Developing Mixed-Reality Serious Geogames

Games and game environments have greatly benefited by the recent developments of mixed-reality that has the potential to build virtual communities, enhance interactions and expand players 'experience. Players can meet in a virtual community space, enjoy sharing and exploring it with other players and holographic avatars. MR games use virtual reality (VR) and augmented-reality (AR) combined with the real world. Objects and actions from the real world can affect simulated objects in a mixed-reality environment. The augmented reality glasses can create the illusion that virtual worlds are actually mixed with the real world in front of the user. According to Souza de Silva and Sutko (de Souza e Silva and Sutko 2009), the defining characteristic of such games is their "lack of primary play space; these games are played simultaneously in physical, digital or represented spaces (such as a game board)". Mixed-reality has been used in applications across fields including healthcare, entertainment, education, design, robotics and other application areas.

Mixed-reality applications require the use of a headset like for virtual-reality (VR). These headsets are also equipped with a camera which can scan users' surroundings. Virtual-reality games cannot be considered mixed-reality games, because they take place only in virtual reality. Figure 2 shows a demonstration of the use of the Microsoft augmented-reality glasses HoloLens, which include sensors, advanced optics and holographic processing to create holograms that appear as real objects for the player (Hughes 2015). In this way they can create an illusion of the virtual world. The implementation can be accomplished in Minecraft environments and projected on a table equipped with a map of the area. These environments can be designed in the form of buildings, urban furniture, or game characters. HoloLens also enables voice commands and supports gestures which contributes to an immersive experience for the player. Competitors such as Oculus Rift and HTC Vive Pro Eye enable higher quality visuals than HoloLens, but no voice commands or gestures. Possible technical challenges associated with mixed-reality implementations include tracking accuracy, latency, and processing power. They can impact the users 'experience and make it difficult for developers to create immersive MR applications.

3.3 Augmented-Reality Geogames

Augmented-reality (AR) adds a layer with digital elements over physical elements, often by using the camera on a smartphone. It superimposes a computer-generated image onto the view of the real world as seen through a headset or mobile device (N.A. 2016). In this way AR enhances the real world with computer-generated content. This interactive experience can be achieved by using software applications combined with hardware such as augmented-reality glasses. Microsoft's HoloLens technology enables multiple



Fig. 2. Mixex-reality game environments (Hughes 2015)

applications including gaming, collaborating on documents and analytics. The first AR technology was developed in 1968 at Harvard when computer scientist Ivan Sutherland, often named the "father of computer graphics", proposed an AR head- mounted display system.

Pokémon Go, an augmented-reality game, is one of the most successful examples of the implementation of AR technology (Fig. 3). It utilizes a geographic information system (GIS) to provide mapping with locations of Pokémon characters. A GIS is a system that enables storing, organizing, analyzing, and visualizing geospatial data. It also uses OpenGL for Embedded Systems (OpenGL ES) for rendering the graphics of Pokémon characters in 3D created with the help of Maya. Pokémon GO implemented a real-time AR, which is a live direct or indirect view of a physical, real-world environment whose elements are augmented by a computer-generated sensory input such as sound, video, graphics, or GPS data. A player first navigates to a location using GIS and hovers



Fig. 3. Pokémon Go using augmented reality in a smart phone (Pokémon Go 2024)

the camera in the selected area. The virtual and playful characters are then extracted from the game library and rendered on video frame as a superimposed model using OpenGL ES.

4 Artificial Intelligence for Digital Serious Geogames

Artificial intelligence (AI) is developing very fast. This section looks only into three selected AI areas that may greatly benefit serious digital geogames. These three areas include virtualized geometry, procedural content generation, and modeling player's behavior.

4.1 Virtualized Geometry

Virtualized geometry represents an exciting opportunity for geogames due to its ability to enable very realistic visualizations of landscapes. For example, Unreal Engine 5 developed by Epic Games brings innovations in visualizations that are very relevant for the implementations in geogames. Its virtualized geometry system Nanite "uses a new internal mesh format and rendering technology to render pixel scale detail and high object counts. It intelligently does work on only the detail that can be perceived and no more. Nanite's data format is also highly compressed and supports fine-grained streaming with automatic level of detail," (Nanite 2024). It can produce highly realistic visualizations of landscapes, cities and other game environments as Fig. 4 demonstrates. The benefits that Nanite brings to the geogames field are mostly related to its visualization capabilities. It is now possible to directly import photogrammetry scans into Nanite/Unreal Engine 5.3 which is of incredible value for geogames and urban AI enabled visualizations. Geoinformation science sector and industry possess many of such scans and they could be effectively used to create dynamic and interactive geogame environments. Applications relevant for STEM learning, urban planning, community engagement and planning for smart and sustainable cities with the help of technologies may greatly benefit from this new technological advancement. Additionally, film-quality source arts, such as ZBrush sculpts, can also be imported for the benefits of realistic visualizations of the selected environments.

4.2 Procedural Content Generation (PCG)

Procedural generation (proc-gen) in computing is a method of creating data with the help of computer algorithms. The term "procedural" refers to the ability of a computer to process a particular function. In video games it can be used to automatically create large amounts of content. PCG is typically considered a feature of digital games and refers to the use of a formal algorithm to generate game content that would typically be produced by a human (Smith 2015). Research on PCG has approached the subject of game artificial intelligence framed as an AI problem of how to replicate human creativity in a computer-based system, how to enable AI to reason about the quality of the created content, and how to build an AI system that can interact with players (Liapis, Yannakakis and Togelius 2013, Smelik et al. 2010, Smith, Whitehead and Mateas 2011).



Fig. 4. Nanite's visualizations of city scenes (Nanite 2023)

Game content created by AI in an automatic way may include in-game generation of 3D models, landscapes, fractals, interactive stories, changing and enhancing environmental conditions, creating game levels, quests, characters, items, game rules, or even changing music depending on the player's playstyle.

An example could be an AI generated conditions in the e-*footprints* energy game (Poplin 2020), a game that invites players to immerse themselves in a city, neighborhood, and finally in their own home (Fig 5). The players can manipulate conditions related to energy in a simulated room environment. They may be surprised by some extreme conditions such as, for example, extreme heat or extreme cold. These new situations are generated on the spot in real-time. The *e-footprints* energy game gives players a variety of options on how to react to those newly generated conditions. The data registering players 'choices is then stored in the back end and can be further analyzed with various data mining and machine learning algorithms. In this way, researchers can study human behavior related to energy consumption.

The newly generated content can also lead to new versions of the game and may result in a high replay value of the game making it interesting and exciting to play. "Moreover, if new content can be generated with sufficient variety, quality, and quantity, then it may become possible to create truly endless games with ultimate replay value. Finally, when content generation is associated with aspects of play, we can expect personalized and adaptive play to emerge via the modification of content" (Yannakakis and Togelius 2018), p. 24). An additional advantage is that it may enable game designers to create unpredictable and therefore very immersive and engaging games based on the concept of conflict, tension, unexpected turns and challenges in AI enhanced games (Togelius et al. 2011, Shaker et al. 2016).

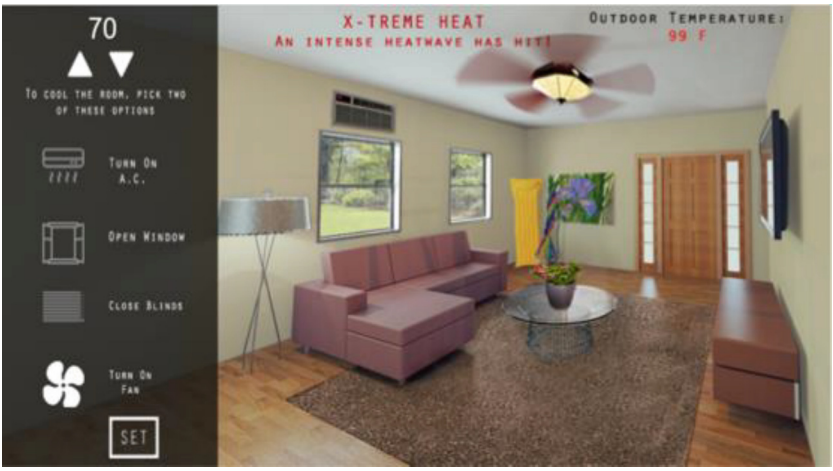


Fig. 5. Extreme heat condition in *e-footprints* energy game (Poplin 2020)

4.3 Games Adapting to the Players' Behavior

Adapting games to the players 'behavior can be accomplished in several ways; by devices measuring biometric feedback and giving feedback directly into the game; data about the gameplay can be stored in the back-end of the game registering decisions made by the players; statistics and analytical functions of the game may be implemented regularly monitoring the players actions in the game. Registering players 'behavior enables the new game content to be adapted to their needs, skills and playstyle and to create player-adaptive games. It can be used to increase the conflict in the game, enjoyment of players, or to maximize learning in a serious game. In the case of a game in which the created content is adaptive, personalized player-centric games refer to experience-driven content. S games may be referred to as player-adaptive games. The opposite of this, in which content generation does not take player's experience into account, is referred to as experience-agnostic.

New developments in hardware and software are fundamental for the inclusion of biofeedback in the concept of modern games. It can include the use of special cameras such as Intel RealSense, which enables depth and tracking capabilities. Nevermind game (2015) is an example of a player-adaptive game. The player is an expert in healing repressed mental trauma. The game was designed to be played with biometric feedback, although it is optional. As the player gets more stressed playing the game, the game gets more difficult, harder to play, the screen may get foggy and unsteady and the navigation in the game may become more difficult for the player.

5 AI Opportunities for Serious Digital Geogames

Artificial Intelligence with its novel tools and capabilities offers a series of opportunities for further development of serious digital geogames. Table 1 summarizes some of these opportunities in the three potential areas of further development including virtualized geometry, procedural content generation, and modeling player's behavior. The first

column summarizes implementations that are relevant for Serious Digital Geo-games. The following columns include the implications for these implementations in the recent developments in AI and the novel capabilities these systems bring with them.

Table 1. Opportunities for Serious Digital Games provided by AI capabilities

Implementations relevant for Serious Geogames	Virtualized geometry	Procedural content generation	Modeling player's behavior
Visualizations of different perspectives	Very realistic visualizations	The content can start with simple concepts and be gradually added to present more complex situations	Visualizations created specifically for the needs of the user or based on the user's experience
Immersive content	Future projections can be added in visualizations What-if scenarios can be visualized	Game elements can be added	Based on the pre-knowledge of the player the content can be presented Biometric feedback can be taken into consideration to engage the users on an emotional level
Responding to the state of the user/player	Simple visualizations can be gradually expanding to more complex	Generated content adjusts to the needs and skills of the user/player	Biometric feedback can be taken into consideration to engage the users on an emotional level
Experiments and new views: future projections and scenarios	Creation of visions, future projections, developments, opportunities, scenarios	The content gets gradually more complex	Depending on the user's biometric feedback new landscapes and projections for the future are created
Learning about the specific topic	Visualizations enable exploring, interacting, asking questions, retrieving data	The more the users learn, the more difficult the content gets	The content is adjusted to the knowledge base of the user
Community engagement and discussions	Create spaces for discussions, topics of discussions	Add role-playing and other game-based concepts and principles	

6 Conclusions and Further Research

Artificial intelligence tools are developing at an incredible speed. They offer new possibilities for further development of serious digital geogames. Their value mostly lies in enabling serious digital geogames to be more immersive and creating engaging and playful content that can be adapted to the players 'behavior and players 'interaction with the computer-based system.

This article suggests studying mixed-reality, including augmented-reality, as one of the most promising technological advancements that can significantly change design, implementation ideas, and principles for serious digital geogames. Mixed-reality concepts can expand the possibilities of digital geogame implementations, inspire their design and improve game mechanics. Especially interesting may be realistic visualizations of cities or neighborhoods in the context of community engagement and discussions about the future of these places.

Artificial intelligence offers some very inspiring possibilities. This article summarizes ideas in virtualized geometry, procedural content generation, and modeling players 'behavior. Virtualized geometry as developed within Unreal Engine enables very realistic visualizations of landscapes which is often an advantage for serious digital geogames. Their environments often take the player to a particular place or real-world situation. Such realistic visualizations can simulate environments and enable the player to imagine real-world situations. Procedural content generation (PCG) adds additional possibilities in the mechanics of serious digital geogames and in ways that they entice and immerse players to keep on coming back to the game and play more. PCG can automatically create new levels, add surprising and unexpected events, start competitions, provide awards, and add characters or music to the existing content. It is the magic of the game and artificial intelligence that play with possibilities in the design and mechanics that keeps the player engaged. Mechanisms can be implemented that invite and stimulate players to return to the game and keep on playing and exploring. Modern games may also explore the connection with the player and register and track their situation and status based on the received biometric feedback. Such geogames and their mechanics can be based on the data received from the biometric measurements of the players and can respond to their emotional and physical states.

It is a beginning of this new era, a revolution in possibilities offered by novel technologies, especially artificial intelligence. Serious digital geogames have yet to make these advancements reality. Geogames usually take years to design and develop and a whole team is needed for their implementation. AI developments are fast and at times unpredictable. The research field of geogames and geoinformation science can greatly benefit from these developments.

Acknowledgments. Thank you to Maria Freeman for the improvement of the language and final edits of this article.

References

Abt, C.: Serious Games. The Viking Press, New York (1970)

Ahlqvist, O., Ramanathan, J., Loffing, T., Kocher, A.: Geospatial human-environment simulation through integration of massive multiplayer online games and geographic information systems. Trans. GIS **16**, 331–350 (2012)

Ahlqvist, O., Schlieder, C.: Geogames and Geoplay. Game-Based Approaches to the Analysis of Geo-Information. Part of the Advances in Geographic Information Science book series (AGIS). Springer (2018)

Artaud, A.: The Theatre and its Double Trans. New York: Grove Weidenfeld: Mary Caro- line Richards (1958)

Ben Hiba, M., et al.: P3 Project: Playful Public Participation. Supervision: A. Poplin Hamburg: HafenCity University Hamburg (2009)

de Andrade, B.: Climate Geogames: a new paradigm to games as civic engagement tools for urban heritage sustainability. Int. J. Environ. Resilience Res. Sci. **2** (2020)

de Andrade, B., Crowley, S., Cocco, C., McNally, B.: A Videogame for Architectural Design? Minecraft for Young People to Imagine Desirable Climate Futures. In: Communications in Computer and Information Science (Videogame Sciences and Arts. VJ 2023). Berlin, Germany: Springer Nature Switzerland (2024)

de Andrade, B., de Sena, Í.S., Moura, A.C.M.: Tirolcraft: The quest of children to playing the role of planners at a heritage protected town. In: Heritage, D. (ed.) Progress in Cultural Heritage: Documentation, Preservation, and Protection, 6th International Conference, EuroMed 2016, pp. 825–835. Springer International Publishing, Nicosia, Cyprus (2016)

de Andrade, B.A.: Planning, children and games: geodesign in the identification of quotidian and symbolic values in the territory. Federal University of Minas Gerais, Belo Horizonte (2019)

de Sena, Í.S., Poplin, A., de Andrade, B.A.: A framework for a serious educational geo-game using Minecraft for landscape exploration. In: Geertman, S., Pettit, C., Goodspeed, R., Staffans, A. (eds.) Urban Informatics for Future Cities. Springer International Publishing (2021)

de Souza e Silva, A.E., Sutko, D.M.E.: Digital Cityscapes: Merging Digital and Urban Playspaces (Digital Formations). Peter Lang Inc., International Academic Publishers; New edition (July 30, 2009)

Devisch, O.: Should planners start playing computer games? arguments from simcity and second life. Plan. Theory Pract. **9**, 209–226 (2008)

Foroughi, M., de Andrade, B., Pereira Roders, A., Wang, T.: Public participation and consensus-building in urban planning from the lens of heritage planning: A systematic literature review. Cities Int. J. Urban Policy Plann. **135** (2023)

Gordon, E., Manosevitch, E.: Augmented deliberation: merging physical and virtual interaction to engage communities in urban planning. New Media Soc. **13**, 75–95 (2010)

Hughes, N.: Microsoft demos 'mixed reality gaming' capabilities of HoloLens with Mine- craft (2015)

Krek, A.: Games in Urban Planning: The Power of Playful Public Participation. In: Mobility Nodes as Innovation Hubs. Proceedings of 13th International Conference on Urban Planning, Regional Development and Information Society, ed. u. a. Manfred Schenk, pp. S. 683–669. ISBN: 978-39502139-5-9. Schwechat-Rannersdorf. Krueger, M. 1983. Artificial reality. Addison-Wesley (2008)

Liapis, A., Yannakakis, G.N., Togelius, J.: Sentient sketchbook: computer-aided game level authoring. In: ACM Conference on Foundations of Digital Games. Chania, Crete, Greece (2013)

Minecraft. 2024. Minecraft games

N.A.: How "Pokémon GO" Took Augmented Reality Mainstream. School of the University of Pennsylvania, Knowledge of Wharton (2016)

Nanite. Nanite Virtualized Geometry (2024)

Newton, A.: Is the Metaverse Already Obsolete? (2023)

O'Brien, M., Chan, K.: Explainer: What is the metaverse and how will it work? OceanRift. 2023. Ocean Rift. The world's first VR aquatic safari park (2021)
Pokémon Go: Pokémon Go website (2023)
Poplin, A.: Playful public participation in urban planning: a case study for online serious games Computers, Environment and Urban Systems (CEUS). Elsevier **36**, 195–206 (2012)
Poplin, A.: Digital serious game for urban planning: B3 – Design your Marketplace!, environment and Planning B: Planning and Design. Environ. Plann. B. Plann. Des. **41**, 493–511 (2014)
(2020) Big Data and Occupants Behavior in a Built Environment: Introducing a Game-Based Data Collection Method. Journal of Urban Planning and Development (JUPD), Special Issue on Data Science & the Built Environment*,* 146
Poplin, A., Schwartz, D.: Special Issue "Gaming and Geospatial Information". In: A special issue of ISPRS International Journal of Geo-Information (ISSN 2220-9964) (2020)
Randal, C., Lasansky, M.D.: Playing Place. Board Games, Popular Culture, Space. The MIT Press, Cambridge (2023)
Ritterbusch, G.D., Teichmann, M.R.: Defining the metaverse: a systematic literature review. IEEE Access **11**, 12368–12377 (2022)
Ritterfeld, U., Cody, M., Vorderer, P.: Serious Games: Mechanisms and Effects. Routledge, New York and London (2009)
Schlieder, C., Kiefer, P., Matyas, S.: Geogames: A Conceptual Framework and Tool for the Design of Location-Based Games from Classic Board Games. In: Proc. of the First International Conference on Intelligent Technologies for Interactive Entertainment (INTETAIN), ed. M. e. a. Maybury, 164–173 Madonna di Campiglio, Italy: Springer, Heidelberg (2005)
Schlieder, C., Kiefer, P., Matyas, S.: Geogames: Designing location-based games from classic board games, pp. 40–46. IEEE, In Intelligent Systems (2006)
SecondLife. Second Life virtual immersive environment (2023)
Shaker, N., Togelius, J., Nelson, M.: Procedural Content Generation in Games. Springer, Cham (2016)
Smelik, R.M., Tutenel, T., de Kraker, K.J., Bidarra, R.: Integrating procedural generation and manual editing of virtual. worlds. In: 2010 Workshop on Procedural Content Generation in Games (co-located with FDG 2010. Monterey, California, USA (2010)
Smith, G.: Understanding procedural content generation: a design-centric analysis of the role of PCG in games. In: Proceedings of the 2014 ACM Conference on Computer- Human Interaction. Toronto, Canada (2014)
An Analog History of Procedural Content Generation. In: Proceedings of the 10th In- ternational Conference on the Foundations of Digital Games (FDG 2015). Pacific Grove, CA, USA (2015)
Smith, G., Whitehead, J., Mateas. M.T.: Reactive planning and constraint solving for mixed-initiative level design. IEEE Transactions on Computational Intelligence and AI in Games (TCIAIG), Special Issue on Procedural Content Generation (2011)
Steinitz, C.: A Framework for Geodesign. Changing Geography by Design. ESRI, Redlands, CA (2012)
Togelius, J.: Playing Smart. On Games, Intelligence, and Artificial Intelligence. Cambridge, Mssachusetts: The MIT Press (2018)
Togelius, J., Kastbjerg, E., Schedl, D., Yannakakis, G.N.: What is procedural content generation?: Mario on the borderline. In: PCGames '11: Proceedings of the 2nd International Workshop on Procedural Content Generation in Games, pp. 1–6 (2011)
Tucci, L.: What is the metaverse? An explanation and in-depth guide (2023)
Yannakakis, G.N., Liapis, A., Alexopoulos, C.: Mixed-initiative co-creativity. In: Proceedings of the 9th Conference on the Foundations of Digital Games (2014)
Yannakakis, G.N., Togelius, J.: Artificial Intelligence and Games. Springer Cham (2018)

Mapping Emotional Landscapes: Understanding the Interplay of Emotions and the Built Environment in Potenza, Italy

Beniamino Murgante[1], Giovanni Mazzarelli[1], Claudia Hedwig van der Laag Yamu[2], and Alfonso Annunziata[1(✉)]

[1] University of Basilicata, 85100 Potenza, Italy
alfonso.f.annunziata@google.com
[2] Oslo Metropolitan University, 0176 Oslo, Norway

Abstract. The emotional responses of individuals to the built environment is a central aspect in developing strategies for urban regeneration, in particular in the context of the pandemic and environmental crises. Emotional responses are not only integral to personal quality of life but also influence urban practices. Concepts aimed at fostering sustainable, inclusive, and vibrant urban areas, hinge upon fostering positive emotional experiences. Understanding how people perceive urban spaces is central to promoting active mobility and social interaction. This study focuses on two districts in Potenza, Italy, examining the distribution of emotional responses and identifying built environment factors that influence individuals' reactions. The study operates on the premise that built environment factors elicit distinct emotions, which, in turn, impact individuals' practices and motivations. Ultimately, this understanding informs strategies for urban regeneration, emphasizing diversity, density, proximity, sustainable mobility, and resilience.

Keywords: PPGIS · Emotional Response · Space Syntax · Place Syntax

1 Introduction

Individuals' emotional response to the built environment represents a central aspect to developing actions of urban regeneration in the context of the post-pandemic scenarios and the environmental crisis. Emotional response, defined as a set of interdependent reactions function of a state of arousal and of its evaluation, is relevant per se, as a component of life satisfaction and individual quality of life and as a factor mediating individual practices. As a result, it emerges as a central concern to the realization of urban concepts, including the 15-minutes city, aimed at constructing sustainable, resilient, inclusive, vital and just cities.

The article is the result of the joint work of the authors. In particular, Beniamino Murgante oversaw the conceptualisation and the supervision of the study and wrote the 'Introduction' and Discussion and Conclusion. Giovanni Mazzarelli oversaw data collection and data analysis. Alfonso Annunziata oversaw the methodology, data analysis and data visualization and wrote the 'Methodology' and 'Results' sections. Claudia Hedwig van der Laag oversaw the supervision and validation of the study and wrote the 'Literature Review'.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 202–217, 2024.
https://doi.org/10.1007/978-3-031-65238-7_14

These concepts, in fact, are based on criteria of density and diversity of functions, optimization of services provision and population density, incentivization of active mobility, integration of ecological infrastructures and urban structures, and resignification of urban spaces as places of sociality. In this perspective, positive emotional responses to the built environment can increase people's propensity to opt for active mobility solutions and to engage in recreational and social activities in urban spaces. As a result, the proposed study is focused on urban concepts based on criteria of density, diversity, proximity, sustainable mobility and investigates and is aimed at: i) understanding the distribution of individuals' emotional responses to urban spaces in two districts of the City of Potenza, in Italy; ii) identifying built environment configurational, structural and functional factors related to the distribution of emotional responses. The study is based on three premises: i) built environment factors elicit specific emotional responses; ii) emotional responses influence individuals' motivation and actions, including travel practices and intention to engage in recreational and social activities in urban spaces; iii) understanding relations among built environment factors, emotions and individual practices is relevant to the definition of actions of urban regeneration based on criteria of diversity, density, proximity, sustainable mobility and resilience. The article is articulated on six sections. After the introduction, Sect. 2 presents an analysis of the literature on basic emotions, emotions' impact on individual practices and on urban concept based on criteria of diversity, density, proximity and sustainable mobility. The methodology is described in Sect. 3 and Sects. 4 and 5 present and interpret the results of the analysis. Lastly, the conclusions section underlines the implications of the findings of the study and outlines its future development.

2 Literature Review

The analysis of the literature is focused on three aspects: i) definition of basic emotions and emotional response; ii) the influence of emotional response on individual practices, including travel practices; iii) urban concepts based on criteria of density, diversity, proximity and sustainable mobility. A fundamental definition of Emotional response is provided by Schachter and Singer [1]. Emotions are conceptualized as a reaction function of a state of arousal and of a cognition relevant to the perceived stimulus. The evaluation of a set of stimuli, resulting in alterations of a person's state, and influencing a reaction is central to the definition of emotion intrinsic to the component process model [2]. The cognitive evaluation of the significance of a person-environment interaction is also central to the definition of emotion proposed by Lazarus [3].

In urban studies, emotional response to built environment factors emerge as an aspect of life satisfaction and individual quality of life [4]. A conceptual model proposed by Mouratidis [5] identifies emotional responses, as a factor mediating the influence of the built environment on life satisfaction. Studies on pedestrians' satisfaction [6, 7], residential satisfaction [8–10], emotional response to environmental stimuli [11, 12] underline the influence of the experience of the built environment on individual practices, life satisfaction and quality of life. Regarding emotional responses, Mouratidis identifies contentment, pleasure, and fear as relevant emotional states [5]. Resch et al. [13] individuate contentment, sadness, fear, and anger/disgust as basic emotional states.

Birenboim and Weijs-Perrée et al. [11, 14], conceptualize emotional responses in terms of security, comfort, contentment, and frustration, elicited by situational variables and environmental factors. Emotional responses' influence on individuals' actions can represent a relevant factor for incentivizing active travel, and people's engagement in activities in urban spaces. Bornioli et al. [15] build on Russell's definition of affective state [16] to demonstrate the influence of individual's emotions elicited by the built environment on their propensity to walk. Gatersleben and Uzzell [17] observes the influence of affect on individual practices and intentions and, as a result, the relevance, to policies aimed at promoting sustainable mobility, of understanding factors influencing individuals' travel experience and the motivation of individuals' preference of specific travel modes. Similarly, Ferreira [18] demonstrated that perceived built environment qualities, including its spatial structure and social environment, can impact residents' walking practices and intentions, and that these effects are mediated by residents' emotional relation to the district. Lastly, De Vos et al. [19] underline the interdependence among perceived environmental qualities, pedestrians' satisfaction, propensity to walk and life satisfaction. The last aspect concerns the criteria informing urban models aimed at realizing sustainable, resilient, inclusive and just cities. Emerging urban questions, concerning spatial injustice, climate alterations, ecological fragility, result in models of social and spatial reorganization of cities focused on ensuring access to urban resources and services, participation, sustainable mobility, ecological resilience [20–24]. In this context, the 15-minutes city concept has emerged as a relevant model for reorganizing urban areas in the post-pandemic scenario [25, 26]. The 15-minutes city concept aims to ensure that basic amenities are located at a distance equivalent to a travel time of 15-minutes from one' residence, so as to reduce dependency on cars and promote mobility solutions based on public transit and active mobility. Antecedents of the 15-minutes city model, including the Neighbourhood Unit Concept (NUC) [27, 28], New Urbanism [29, 30], transit-oriented development (TOD) [31–34], and neo-traditionalist design [35, 36], also propose compact, mixed-use, and pedestrian-centered urban structures. As a result, the founding criteria of these models include proximity, density and diversity. More precisely, Density refers to the optimal number of residents required to sustain a variety of services, Proximity underlines the spatial closeness of services of general interest, and Diversity refers to the combination of distinct urban functions and identities, fostering social interactions and quality of life. Lastly, Density, diversity and proximity to amenities are identified as factors conducive to active travel and recreational activities in urban spaces [37–40], and as factors conducive to positive health outcomes [41–44]. As a consequence, this study builds on the concept of interdependence among macro-scale built environment factors, pedestrians' experience and propensity to opt for active travel, and investigates the correlation among individuals' emotional response to the built environment and macro-scale built environment properties of density, proximity, diversity and accessibility.

3 Methodology

The objective of the study is the assessment of the frequency of emotional responses across public spaces and of the correlation among emotional responses' distribution and macro- and meso-scale properties of the built environment. As a result, the methodology

integrates Public Participation GIS techniques, spatial analysis and statistical analysis, and is articulated on five stages: i) reconstruction of a spatial dataset related to the distribution of services of general interest; ii) formulation of a map-based survey and analysis of survey's results; iii) computation of indices of configurational properties; iv) computation of indices of access to points of interest related to specific categories of services of general interest and computation of a synthetic index of coverage of SGIs; v) categorization of spaces based on the prevalence of positive or negative perceptions and characterisation of the resulting types of public spaces.



Fig. 1. Selection of the Area of Study: The Ancient Core and the Poggio Tre Galli District in Potenza, Italy

3.1 Reconstruction of the Spatial Dataset

The analysis focuses on the City of Potenza, in Italy. In particular, the selected areas of study are the Ancient Core, a compact, dense district, presenting a spatial structure organised by the axis of Pretoria street, and a system of transversal streets, or *Quintane*, and the Poggio Tre Galli district, a modernist district presenting a coarser spatial structure organised by spaces designed for motorized mobility, green areas, and semi-private

spaces separating buildings from the urban space (Fig. 1). The analysis focuses on six categories of urban land uses: recreational services, retail activites, sustenance services, public general services, urban green areas and non-built areas. Information related to the distribution of points of interest included in the categories public general services, retail activities, recreational activities, and sustenance services ate retrieved from Google Maps database. Information related to urban green areas and non-built areas are retrieved from the Copernicus Urban Atlas service. Information related to urban services includes the number of reviews and the average users' rating. The segment map is derived from the Road Centre Line map of the City of Potenza, retrieved from the Open Street Map database. A four-step procedure is utilised for constructing the segment map: first, centre lines related to roads not suitable for pedestrian movement are eliminated, including geometries comprised in the categories Arterial, Trunk, bridleway, construction, cycleway, emergency, path, raceway, service, and track. Secondly, the road centre line map is validated by repairing topological errors, via the Road Network Cleaner function of the Space Syntax Toolkit (SST). The sub-sequent step is aimed at converting the edited road-centre line map into a segment map, via the Network Segmenter function of the SST. Lastly, the segment map is edited by eliminating sets of isolated segments. The centroids of the streets' segments intersecting the area of study are selected as units of analysis.

3.2 Formulation of a Map-Based Survey

A map-based survey is created and administered via the Maptionnaire tool. Maptionnaire is a Public Participation GIS tool. Public Participation GIS (PPGIS) tools are a crucial component of urban and regional planning, as they enable the integration of local information and preferences and expert input. Web-based tools enable asynchronous and distributed participation, overcoming the limitations of traditional participatory practices [45–47]. In particular, the utilization of the Maptionnaire tool for investigating people's perception of public spaces is relevant to studies in the fields of urban planning, geography, sociology, and environmental psychology. The Interdisciplinarity underlines the relevance of PPGIS tools for understanding the complex dynamics of the interactions among people and public spaces, involving the dimensions of accessibility, safety, attractiveness, and usability [45, 48–50]. The map-based survey structured for the present study is aimed at retrieving information on locations, across the selected areas of study, associated with specific positive emotions, including contentment, safety, comfort, and negative emotions, including fear, boredom and anger/disgust.

Spatial information related to individuals' experience of public spaces across the areas of study is formalised via geostatistical analysis tools. The spatial lag of the frequency of participants' answers, for each basic emotion is computed for each unit of analysis. The spatial lag is selected as the dependent variable in order to minimise errors resulting from answers' misplacement and to avoid sudden breaks in the answers' distribution.

3.3 Configurational Indicators

Step four consists in the definition and computation of a set of indicators of configurational properties. Configuration refers to the topological relations among elements within a spatial structure. More precisely, it denotes the specific organization of a spatial structure that manifest and perpetuate principles governing social interactions. The interdependence among spatial configurations and social practices is intrinsic to the concepts of movement economy and centrality, which elucidate how urban centers and sub-centers emerge from a process of mutual influences among the distribution of natural movement, location of economic activities, and the layout of the urban environment [20, 21, 51–53]. The study employs centrality metrics to evaluate the influence of the built environment on the intensity of pedestrian activity. Integration measures the distance from each starting point to any potential destination within the environment. It measures a spaces's relevance as a destination. Choice measures the probability that a space is located along the shortest route from each location to any other location within a spatial structure. Hence, it measures the through movement potential of a space, that is, its relevance as a movement space. Distance is quantified as the sum of angular deviation along a route (angular distance) [54]. The radius definition isolates spatial sub-structures around a starting point, enabling the assessment of configurational properties at micro-, meso-, and macro-scales. Moreover, measuring configurational properties at different scales facilitates understanding the impact of the Built Environment on various types of movement. In particular, radii ranging from 400 m to 3000 m are relevant for investigating how configuration influences pedestrian movement [55]. Moreover, Visibility Graph Analysis (VGA) is used to measure the properties of the visibility graph derived from the spatial layout of the areas of study. More precisely, VGA investigates the visibility relations among individual locations and the entire spatial layout [56]: the aim is understanding the interdependence among perception of space, movement and interaction. The metrics considered include visual integration, defined as the visual distance from each space to any other space, through vision, defined as the number of lines of visibility that intersect a location, visual control, computed, for each location, as the sum of the reciprocals of the number of locations visible from the adjoining cells and isovist compactness, measuring the regularity of the isovist polygon generated for each location [57]. Lastly, the structure of the areas of study is described in terms of Road Intersection density, as a measure of the permeability of the built environment [20, 21, 24, 58], openness and transversal dimension, as measure of the degree of enclosure of individual spaces [59] and Ground Surface Index [20, 21, 39, 60], measuring the local building density around each segment.

3.4 Access to Urban Services

The proximity of urban services to street segments is determined via the Attraction Reach (AR) function of the Place Syntax Tool. The Place Syntax tool is an open-source spatial analysis platform, developed by researchers from the KTH School of Architecture, Chalmers School of Architecture (SMoG), and Spacescape AB. PST integrates Space Syntax Theory into urban environment analysis. By incorporating points of interest defined by spatial coordinates and quantitative data, and the spatial layout defined by

street segments, the tool facilitates the evaluation of accessibility to specific locations. The AR function measures the proximity to the j-th segment of points of interest (POIs) of the i-th category of urban services. The proximity score for each service category is calculated based on the inverse ratio of the distance to the POIs from the segment, within a predetermined radius of 400 m, and is multiplied by a quality factor. The quality factor is computed as the product of the normalized count of reviews by the normalized users' average rating. To quantify urban service coverage, a composite index, the ISG, is introduced. It is calculated as the weighted average of the normalized AR metrics for each service category. The ISG index values range from 0 to 1, and indicate a gradient from limited access to SGIs (values tending to 0) to optimal access to SGIs (values tending to 1). The proposed metrics address limitations of existing measures of proximity and diversity by incorporating in the measurement of conditions of access, a diversity factor, formalised in terms of presence of destinations related to distinct types of SGI, a variety factor, in terms of presence of alternative destinations for each service category, an impedance factor, conceptualised in terms of distance of destinations from the origin point, and a quality factor, formalized in terms of number of reviews and users' average rating.

3.5 Categorization and Characterisation of Segments

An emotional score is computed as the difference between the spatial lag of the frequency of positive emotional responses and the spatial lag of the frequency of negative responses. The segments are then divided into five quintiles based on the values of the emotional score and three conditions are selected for exploratory statistical analysis: spaces presenting a prevalence of positive responses, spaces presenting a prevalence of negative responses and spaces presenting null emotional responses. Segments included in the selected categories are assessed based on significant deviation among average values of the original variables. The Average Chart function is used to assess the significance of the disparity between the mean value of the j-th variable for the i-th subset and the mean value calculated for the rest of the observations. Significance is determined by the p-value derived from the f-statistic obtained from a regression incorporating a binary variable set to 1 for observations included in the i-th subset and 0 for the unselected observations.

4 Results

The results of the survey reveal distributions of the emotional responses specific to each district: In the ancient core, positive emotional response are concentrated in the central section of the district. In particular, a significant cluster of positive responses is located in Mario Pagano square, and secondary clusters can be identified along Pretoria Street and Giacomo Matteotti square: Consequently, the distribution of individuals' emotional response reflects the symbolic, functional relevance of public spaces. In The Poggio Tre Galli district, less intense clusters can be identified along the central, longitudinal axis of the district, and particularly in Europa Unita Park and Costituzione Italiana Square. Vice versa, negative emotions, including fear, anger, boredom are concentrated in marginal/edge areas (Fig. 2).

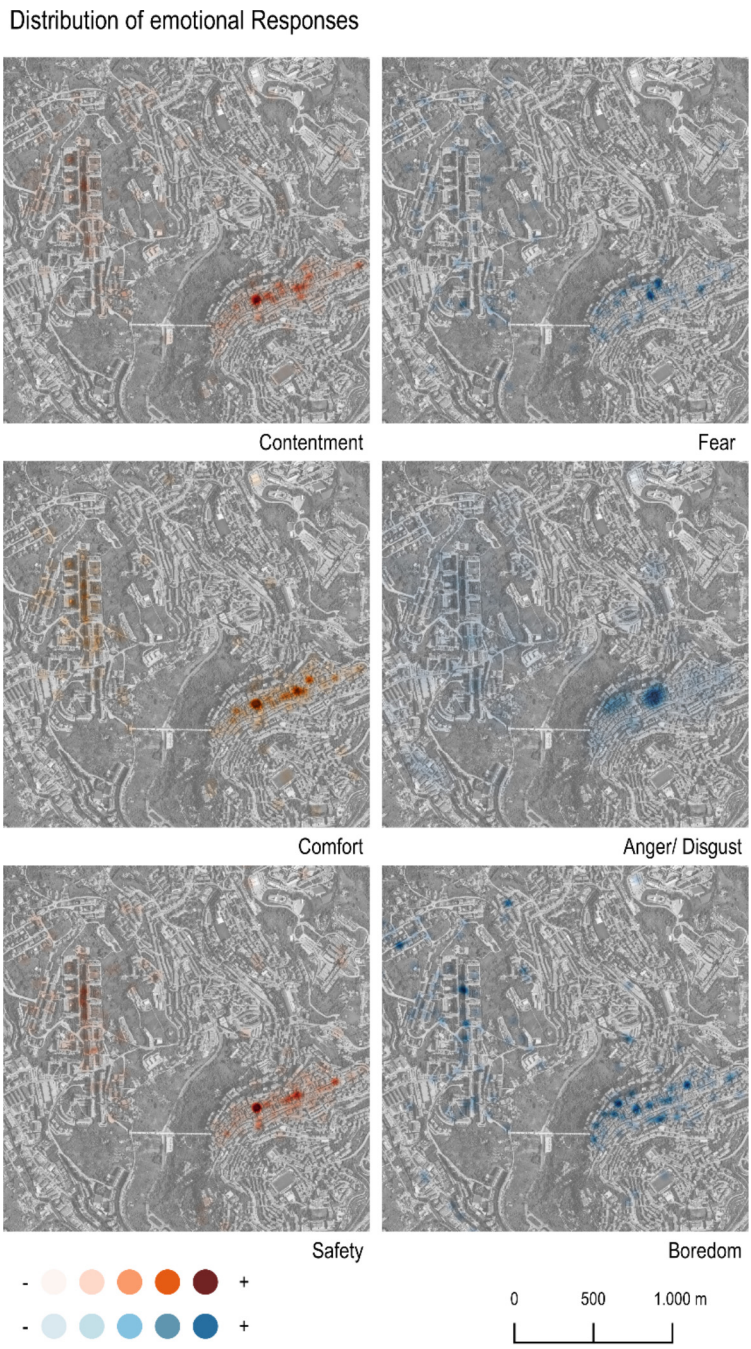


Fig. 2. Distribution of Emotional Responses.

As a result, a similar configuration emerges: A polycentric structure, and an elongated centre in the central section of the areas of study, related to positive emotional response, and a fragmented structure along the edges, related to negative responses (See Fig. 1). Regarding configurational and functional indicators, the ancient core's spatial structure is more permeable, compact and integrated compared to Poggio Tre Galli district (See Fig. 2). Moreover, the spatial layout of the ancient core presents superior levels of enclosure and of street alignment continuity. Angular Integration values underline the emergence of an eccentric core of spaces integrated at the local and macro-scale in the ancient core and a transversal spatial sequence, along Anzio Street, in the Poggio Tre Galli district. The gradient of angular choice values reveals the emergence of Pretoria Street as a central space at the local scale and of Anzio Street at the macro-scale.

Regarding visibility relations, A discontinuous sequence of spaces, along Pretoria street, can be identified in the ancient core, presenting superior levels of integration and isovist regularity. In the Poggio Tre Galli district, a continuous sequence of spaces, along Adriatico street presents similar conditions of visual integration and isovist regularity. Lastly, optimal levels of access to services, measured by the IGS indicator, are observed in the central core of the Ancient District. Inferior levels of access to SGIs are observed in the Poggio Tre Galli district, and result in a polycentric structure, constituted by a central core of spaces presenting adequate levels of service coverage, at the intersection among Anzio Street and the longitudinal axis comprising Europa Unita Park and Unità d'Italia street, and secondary clusters, presenting moderate levels of access to SGIs, along the edge of the district, in particular along Ancona street.

The exploratory analysis of the sub-set of spaces in the last quintile of the emotional score (ES < -0.33) underline significant configurational and functional properties of spaces presenting a prevalence of negative responses. Spaces eliciting negative emotions, in fact, present inferior conditions of permeability, density, and enclosure, indicated by values of the metrics Road Intersection density and Ground Surface Index minor than the average values of the non-selected observations, and by values of openness and transversal dimension above the mean computed for non-selected observations. Moreover, spaces eliciting negative emotions present inferior values of integration, inferior levels of access to general public services, recreational activities, retail activities and sustenance services, and levels of proximity to non-built areas above the mean of non-selected spaces (See Table 1).

Similar conditions are observed in spaces presenting no emotional responses: values of the DRI and GSI metrics, of integration at the meso-and macro-scale and of centrality at the micro-meso- and macro-scale are inferior to the mean computed for non-selected segments. Similarly, inferior levels of access to sustenance services, retail activities and recreational activities are observed in spaces presenting null emotional responses frequency. Consequently, values computed for the ISG are inferior to the mean calculated for non-selected segments. Vice versa, openness, transversal dimension and conditions of proximity to non-built areas are above the mean computed for non-selected spaces (Fig. 3 and Table 1).

Lastly, spaces presenting null emotional response present a more regular street front alignment, compared to segments eliciting participants' emotional response. Lastly, spaces presenting a prevalence of positive responses (ES > 1.78) are more compact

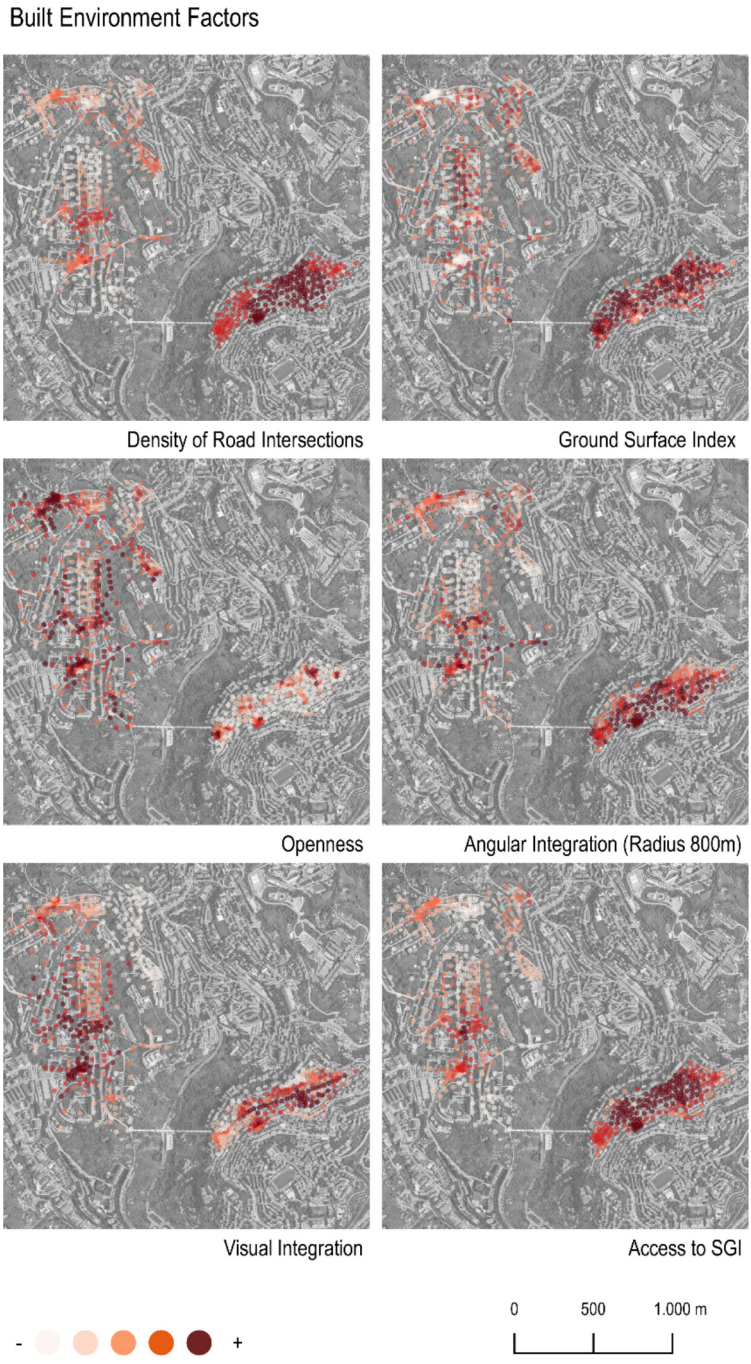


Fig. 3. Distribution of values of metrics of relevant built environment factors

(GSI above the mean of non-selected spaces), permeable, more integrated, in terms of visual relations and characterised by more regular isovists (Table 1).

Moreover, levels of angular integration at the micro and meso-scale (at radius 800 m and 1600 m), centrality at radius 800 m and levels of access to general public services, sustenance services, retail activities and recreational activities, and the composite indicator of access to SGIs present average values above the mean computed for non selected spaces.

Table 1. Results of the Exploratory Analysis of alternative types of spaces

		Negative Response	Positive Response	Null Response
VARIABLE	VALUE	COEF	COEF	COEF
DRI800	Constant	70.225	62.058	68.147
	Deviation	−14.754	26.988	−16.448
GSI	Constant	0.285	0.211	0.272
	Deviation	−0.120	0.256	−0.211
V_INT	Constant	0.521	0.488	
	Deviation	−0.059	0.112	
ME_DE	Constant	0.739	0.718	
	Deviation	−0.039	0.071	
REL_ENT	Constant	0.630	0.603	
	Deviation	−0.049	0.090	
IS_COM	Constant		0.794	
	Deviation		0.037	
AI800	Constant	103.622	99.384	
	Deviation	−6.951	14.777	
AI1600	Constant		221.631	228.190
	Deviation		19.702	−47.611
AI2000	Constant			299.431
	Deviation			−65.010
AI10000	Constant			792.687
	Deviation			−52.477
AC800	Constant		0.095	0.107
	Deviation		0.044	−0.050
AC1600	Constant			0.114
	Deviation			−0.063

(*continued*)

Table 1. (*continued*)

		Negative Response	Positive Response	Null Response
AC2000	Constant	0.081		0.091
	Deviation	0.035		−0.050
AR4GEN	Constant	0.336	0.265	
	Deviation	−0.130	0.237	
AR4RET	Constant	0.262	0.170	0.239
	Deviation	−0.160	0.308	−0.178
AR4GRO	Constant	0.204	0.175	0.201
	Deviation	−0.063	0.082	−0.166
AR4REC	Constant	0.293	0.202	0.272
	Deviation	−0.164	0.301	−0.209
AR4UGA			0.195	
			−0.049	
AR4NBL	Constant	0.162	0.225	0.177
	Deviation	0.141	−0.178	0.235
ISG	Constant	0.241	0.179	0.224
	Deviation	−0.118	0.197	−0.125
ST_AL	Constant	19.074		22.455
	Deviation	10.460		−20.462
W	Constant	30.918	33.991	31.057
	Deviation	4.423	−11.387	13.073
OPEN	Constant	0.708	0.754	0.713
	Deviation	0.073	−0.162	0.168

Interestingly, levels of access to urban green areas and non-built areas are inferior to mean values observed for non-selected spaces. Lastly, spaces eliciting positive emotions present superior levels of enclosure, indicated by average values of the transversal section and openness metrics inferior to the mean computed for non-selected spaces.

5 Discussion and Conclusion

The results conduct to distinct considerations: first, the selected areas of study reflect distint urban paradigms, resulting in specific configurations. The modernist urban development of Poggio Tre Galli presents a spatial structure designed to facilitate motorized transport, resulting in a coarser, sparser and more segregated configuration, defined by open spaces and green areas, and presenting modest levels of access to services.

Vice versa, The ancient core spatial structure is more compact, dense, permeable and integrated, defining enclosed spaces and presenting optimal levels of access to public services, sustenance services, retail activities and recreational activities. Building on previous studies of Italian cities' levels of compliance to the 15-minutes city concept [20, 21], the findings confirm the positive relation among levels of access to services and conditions of streets' enclosure, integration, permeability and compactness.

The distinct spatial configuration results in significant diversity in terms of individuals' perceptions. Observed Emotional responses are more numerous in the ancient core, and determine a positive emotional score, above the mean value computed for the Poggio Tre Galli district. A second consideration regards the potential relation among macro-scale built environment factors and emotional response. More precisely, the results suggest that spatial and visual integration, enclosure, permeability, compactness, and density and diversity of urban functions are factors conducive to positive emotions and perceptions of the built environment. The relevance of the study relies on its contribution to the understanding of the interactions among built environment, individual emotions, and individual and social practices. The study, in fact, underlines the positive potential impact of specific meso- and macro-scale built environment factors on individuals' emotions. The findings are relevant to the development of strategies of urban regeneration: given the importance of emotions per se and as factors influencing modifications in individuals' practices, the study identifies enclosure, permeability, compactness, and density and diversity of urban functions as significant criteria for developing sustainable, inclusive and resilient cities.

Disclosure of Interests. The authors have no competing interests.

References

1. Schachter, S., Singer, J.: Cognitive, social, and physiological determinants of emotional state. Psychol. Rev. **69**, 379–399 (1962). https://doi.org/10.1037/h0046234
2. Scherer, K.R.: Appraisal considered as a process of multilevel sequential checking. Appraisal Process. Emotion Theory Methods Res. **92**, 57 (2001)
3. Lazarus, R.S.: Emotion and Adaptation. Oxford University Press (1991)
4. Annunziata, A., Garau, C., Lotfata, A.: Measuring the potential for meaningful usability of spaces: the case studies of two social housing districts in Cagliari, Italy. In: Gervasi, O., et al. (eds.) Computational Science and Its Applications – ICCSA 2023 Workshops, pp. 256–273. Springer, Cham (2023)
5. Mouratidis, K.: Urban planning and quality of life: A review of pathways linking the built environment to subjective well-being. Cities **115**, 103229 (2021). https://doi.org/10.1016/j.cities.2021.103229
6. Kim, S., Park, S., Lee, J.S.: Meso- or micro-scale? Environmental factors influencing pedestrian satisfaction. Transp. Res. Part D: Transp. Environ. **30**, 10–20 (2014). https://doi.org/10.1016/j.trd.2014.05.005
7. De Vos, J.: Analysing the effect of trip satisfaction on satisfaction with the leisure activity at the destination of the trip, in relationship with life satisfaction. Transportation **46**(3), 623–645 (2017). https://doi.org/10.1007/s11116-017-9812-0
8. Cao, J., Hao, Z., Yang, J., Yin, J., Huang, X.: Prioritizing neighborhood attributes to enhance neighborhood satisfaction: an impact asymmetry analysis. Cities **105**, 102854 (2020). https://doi.org/10.1016/j.cities.2020.102854

9. Cao, X. (Jason), Wang, D.: Environmental correlates of residential satisfaction: an exploration of mismatched neighborhood characteristics in the Twin Cities. Landscape Urban Plann. **150**, 26–35 (2016). https://doi.org/10.1016/j.landurbplan.2016.02.007
10. Kourtit, K., Nijkamp, P., Wahlström, M.H.: How to make cities the home of people – a 'soul and body' analysis of urban attractiveness. Land Use Policy **111**, 104734 (2021). https://doi.org/10.1016/j.landusepol.2020.104734
11. Weijs-Perrée, M., Dane, G., van den Berg, P.: Analyzing the relationships between citizens' emotions and their momentary satisfaction in urban public spaces. Sustainability **12**, (2020). https://doi.org/10.3390/su12197921
12. Su, L., Zhou, S., Kwan, M.-P., Chai, Y., Zhang, X.: The impact of immediate urban environments on people's momentary happiness. Urban Stud. **59**, 140–160 (2022). https://doi.org/10.1177/0042098020986499
13. Resch, B., Summa, A., Zeile, P., Strube, M.: Citizen-centric urban planning through extracting emotion information from twitter in an interdisciplinary space-time-linguistics algorithm. Urban Plann. **1**(2) (2016): Volunteered Geographic Information and the City (2016). https://doi.org/10.17645/up.v1i2.617
14. Birenboim, A.: The influence of urban environments on our subjective momentary experiences. Environ. Plann. B: Urban Anal. City Sci. **45**, 915–932 (2018). https://doi.org/10.1177/2399808317690149
15. Bornioli, A., Parkhurst, G., Morgan, P.L.: Affective experiences of built environments and the promotion of urban walking. Transp. Res. Part A: Policy Practice. **123**, 200–215 (2019). https://doi.org/10.1016/j.tra.2018.12.006
16. Russell, J.A.: Core affect and the psychological construction of emotion. Psychol. Rev. **110**, 145–172 (2003). https://doi.org/10.1037/0033-295X.110.1.145
17. Gatersleben, B., Uzzell, D.: Affective appraisals of the daily commute: comparing perceptions of drivers, cyclists, walkers, and users of public transport. Environ. Behav. **39**, 416–431 (2007). https://doi.org/10.1177/0013916506294032
18. Ferreira, I.A., Johansson, M., Sternudd, C., Fornara, F.: Transport walking in urban neighbourhoods—impact of perceived neighbourhood qualities and emotional relationship. Landsc. Urban Plan. **150**, 60–69 (2016). https://doi.org/10.1016/j.landurbplan.2016.02.009
19. De Vos, J., Lättman, K., van der Vlugt, A.-L., Welsch, J., Otsuka, N.: Determinants and effects of perceived walkability: a literature review, conceptual model and research agenda. Transp. Rev. **43**, 303–324 (2023). https://doi.org/10.1080/01441647.2022.2101072
20. Murgante, B., Patimisco, L., Annunziata, A.: Developing a 15-minute city: a comparative study of four Italian Cities-Cagliari, Perugia, Pisa, and Trieste. Cities **146**, 104765 (2024). https://doi.org/10.1016/j.cities.2023.104765
21. Murgante, B., Valluzzi, R., Annunziata, A.: Developing a 15-minute city: Evaluating urban quality using configurational analysis. The case study of Terni and Matera, Italy. Appl. Geography **162**, 103171 (2024). https://doi.org/10.1016/j.apgeog.2023.103171
22. Barbarossa, L.: The Post Pandemic City: challenges and opportunities for a non-motorized urban environment. An Overview of Italian Cases. Sustainability. **12** (2020). https://doi.org/10.3390/su12177172
23. Jasiński, A.: COVID-19 pandemic is challenging some dogmas of modern urbanism. Cities **121**, 103498 (2022). https://doi.org/10.1016/j.cities.2021.103498
24. Garau, C., Annunziata, A.: A method for assessing the vitality potential of urban areas. The case study of the Metropolitan City of Cagliari, Italy. City, Territory and Architecture. 9, 7 (2022). https://doi.org/10.1186/s40410-022-00153-6
25. Allam, Z., Bibri, S.E., Chabaud, D., Moreno, C.: The '15-Minute City' concept can shape a net-zero urban future. Humanities Soc. Sci. Commun. **9**, 126 (2022). https://doi.org/10.1057/s41599-022-01145-0

26. Moreno, C., Allam, Z., Chabaud, D., Gall, C., Pratlong, F.: Introducing the "15-Minute City": sustainability, resilience and place identity in future post-pandemic cities. Smart Cities. **4**, 93–111 (2021). https://doi.org/10.3390/smartcities4010006
27. Kissfazekas, K.: Circle of paradigms? Or '15-minute' neighbourhoods from the 1950s. Cities **123**, 103587 (2022). https://doi.org/10.1016/j.cities.2022.103587
28. Perry, C.: The neighborhood unit. In: The City Reader, pp. 607–619. Routledge (2015)
29. Ellis, C.: The new urbanism: critiques and rebuttals. J. Urban Des. **7**, 261–291 (2002). https://doi.org/10.1080/1357480022000039330
30. Katz, P.: The New Urbanism: Toward an Architecture of Community. McGraw-Hill, Incorporated, New York, United States (1994)
31. Calthorpe, P.: The Next American Metropolis. Ecology, Community and the American Dream. Princeton Architectural Press, New York, United States (1993)
32. Cervero, R., Radisch, C.: Travel choices in pedestrian versus automobile oriented neighborhoods. Transp. Policy **3**, 127–141 (1996). https://doi.org/10.1016/0967-070X(96)00016-9
33. Ibraeva, A., Correia, G.H. de A., Silva, C., Antunes, A.P.: Transit-oriented development: a review of research achievements and challenges. Transp. Res. Part A: Policy Practice **132**, 110–130 (2020). https://doi.org/10.1016/j.tra.2019.10.018
34. Knowles, R.D., Ferbrache, F., Nikitas, A.: Transport's historical, contemporary and future role in shaping urban development: re-evaluating transit oriented development. Cities **99**, 102607 (2020). https://doi.org/10.1016/j.cities.2020.102607
35. Duany, A., Plater-Zyberk, E.: The second coming of the American small town. Wilson Quarterly. **16**, 3–51 (1992)
36. Ryan, S., McNally, M.G.: Accessibility of neotraditional neighborhoods: a review of design concepts, policies, and recent literature. Transp. Res. Part A: Policy Practice **29**, 87–105 (1995). https://doi.org/10.1016/0965-8564(94)E0008-W
37. Blečić, I., Cecchini, A., Congiu, T., Fancello, G., Trunfio, G.A.: Evaluating walkability: a capability-wise planning and design support system. Int. J. Geogr. Inf. Sci. **29**, 1350–1374 (2015). https://doi.org/10.1080/13658816.2015.1026824
38. Cerin, E., Saelens, B.E., Sallis, J.F., Frank, L.D.: Neighborhood Environment Walkability Scale: Validity and Development of a Short Form. Medicine & Science in Sports & Exercise. 38 (2006)
39. Cerin, E., Nathan, A., van Cauwenberg, J., Barnett, D.W., Barnett, A., on behalf of the Council on Environment and Physical Activity (CEPA) – Older Adults working group: The neighbourhood physical environment and active travel in older adults: a systematic review and meta-analysis. Int. J. Behav. Nutr. Phys. Act. **14**, 15 (2017). https://doi.org/10.1186/s12966-017-0471-5
40. Christian, H.E., et al.: How important is the land use mix measure in understanding walking behaviour? results from the RESIDE study. Int. J. Behav. Nutr. Phys. Act. **8**, 55 (2011). https://doi.org/10.1186/1479-5868-8-55
41. Barnett, D.W., Barnett, A., Nathan, A., Van Cauwenberg, J., Cerin, E., on behalf of the Council on Environment and Physical Activity (CEPA) – Older Adults working group: Built environmental correlates of older adults' total physical activity and walking: a systematic review and meta-analysis. Int. J. Behav. Nutr. Phys. Act. **14**, 103 (2017). https://doi.org/10.1186/s12966-017-0558-z
42. Frank, L.D., Schmid, T.L., Sallis, J.F., Chapman, J., Saelens, B.E.: Linking objectively measured physical activity with objectively measured urban form: Findings from SMARTRAQ. Am. J. Prev. Med. **28**, 117–125 (2005). https://doi.org/10.1016/j.amepre.2004.11.001
43. Frank, L.D., Sallis, J.F., Conway, T.L., Chapman, J.E., Saelens, B.E., Bachman, W.: Many pathways from land use to health: associations between neighborhood walkability and active

transportation, body mass index, and air quality. J. Am. Plann. Assoc. **72**, 75–87 (2006). https://doi.org/10.1080/01944360608976725
44. Sallis, J.F., et al.: Physical activity in relation to urban environments in 14 cities worldwide: a cross-sectional study. The Lancet. **387**, 2207–2217 (2016). https://doi.org/10.1016/S0140-6736(15)01284-2
45. Zhang, S.: Public participation in the Geoweb era: Defining a typology for geo-participation in local governments. Cities **85**, 38–50 (2019). https://doi.org/10.1016/j.cities.2018.12.004
46. Brown, G., Kyttä, M.: Key issues and research priorities for public participation GIS (PPGIS): a synthesis based on empirical research. Appl. Geogr. **46**, 122–136 (2014). https://doi.org/10.1016/j.apgeog.2013.11.004
47. Kahila-Tani, M., Kytta, M., Geertman, S.: Does mapping improve public participation? exploring the pros and cons of using public participation GIS in urban planning practices. Landsc. Urban Plan. **186**, 45–55 (2019). https://doi.org/10.1016/j.landurbplan.2019.02.019
48. Harsia, E., Nummi, P.: Beyond the Blind Spot: Enhancing Polyphony Through City Planning Activism Using Public Participation GIS. URBAN PLANNING. **9** (2024). https://doi.org/10.17645/up.7096
49. Kyttä, M., Broberg, A., Tzoulas, T., Snabb, K.: Towards contextually sensitive urban densification: Location-based softGIS knowledge revealing perceived residential environmental quality. Landsc. Urban Plan. **113**, 30–46 (2013). https://doi.org/10.1016/j.landurbplan.2013.01.008
50. Giuffrida, N., Le Pira, M., Inturri, G., Ignaccolo, M.: Mapping with stakeholders: an overview of public participatory GIS and VGI in transport decision-making. ISPRS Int. J. Geo-Inform. **8** (2019). https://doi.org/10.3390/ijgi8040198
51. Hillier, B., Hanson, J.: The Social Logic of Space. Cambridge University Press, Cambridge, United Kingdom (1984). https://doi.org/10.1017/CBO9780511597237
52. Hillier, B.: Space is the machine: a configurational theory of architecture. University College of London, London, United Kingdom (2007)
53. Mohamed, A.A., van der Laag Yamu, C.: Space syntax has come of age: a bibliometric review from 1976 to 2023. J. Plann. Lit. 08854122231208018 (2023). https://doi.org/10.1177/08854122231208018
54. Hillier, B., Vaughan, L.: The city as one thing. Prog. Plan. **67**, 205–230 (2007). https://doi.org/10.1016/j.progress.2007.03.001
55. Dhanani, A., Tarkhanyan, L., Vaughan, L.: Estimating pedestrian demand for active transport evaluation and planning. Transp. Res. Part A: Policy Practice **103**, 54–69 (2017). https://doi.org/10.1016/j.tra.2017.05.020
56. Turner, A., Doxa, M., O'Sullivan, D., Penn, A.: From isovists to visibility graphs: a methodology for the analysis of architectural space. Environ. Plann. B. Plann. Des. **28**, 103–121 (2001). https://doi.org/10.1068/b2684
57. Koutsolampros, P., Sailer, K., Varoudis, T., Haslem, R.: Dissecting Visibility Graph Analysis: The metrics and their role in understanding workplace human behaviour. In: Proceedings of the 12th International Space Syntax Symposium. International Space Syntax Symposium, Beijing, China (2019)
58. Ewing, R., Cervero, R.: Travel and the Built Environment. J. Am. Plann. Assoc. **76**, 265–294 (2010). https://doi.org/10.1080/01944361003766766
59. Ewing, R., Hajrasouliha, A., Neckerman, K.M., Purciel-Hill, M., Greene, W.: Streetscape features related to pedestrian activity. J. Plan. Educ. Res. **36**, 5–15 (2016). https://doi.org/10.1177/0739456X15591585
60. Cervero, R., Kockelman, K.: Travel demand and the 3Ds: density, diversity, and design. Transp. Res. Part D: Transp. Environ. **2**, 199–219 (1997). https://doi.org/10.1016/S1361-9209(97)00009-6

Application of the 15-Minute City Criteria to a Metropolitan Area: The Case Study of the Metropolitan City of Cagliari, Italy

Beniamino Murgante and Alfonso Annunziata(✉)

University of Basilicata, 85100 Potenza, Italy
alfonso.f.annunziata@google.com

Abstract. The necessity for substantial adaptations of the built environment in response to environmental crises and the post-pandemic scenario underscores the critical interaction of urban structure and land-use organization. The study focuses on the concept of the "15-minute city" as a significant model for urban adaptation, aiming to improve access to services of general interest (SGIs), increase ecological resilience, reduce car-dependency, and foster inclusive public spaces. The aim of the study is to evaluate levels of compliance to 15-minute city criteria of the Metropolitan City of Cagliari, Italy, by combining configurational, spatial, and statistical analyses. The findings underline disparities in access to SGIs across distinct parts of the metropolitan area, the emergence of a trans-scalar polycentric structure and underscore the impact of urban form factors on service access levels. In particular, the study identifies density, permeability, and centrality as central aspects for urban regeneration policies aimed at creating inclusive, vibrant urban environments. This study contributes to the operationalization of criteria central to developing urban regeneration strategies based on the principles of the 15-minute city and, consequently, to the present discourse on urban organization.

Keywords: Proximity · 15-Minute city · Built Environment · Urban Area · Place Syntax

1 Introduction

The interaction of urban layout and land-use organization, particularly in the context of environmental crises and the post-pandemic scenario, determines the need for substantial adaptations of the built environment. Fundamental objectives include improving access to services of general interest (SGI), improving urban areas' ecological resilience, reducing car-dependency, promoting active modes of transportation, and fostering inclusive public spaces. The necessity for urban reorganization is underlined by various studies [1–3].

The Article is the result of the joint work of the authors. In particular, Beniamino Murgante oversaw the conceptualization and supervision of the study and wrote the 'Introduction', 'Methodology' and the 'Discussion and Conclusions' sections. Alfonso Annunziata oversaw data collection, data analysis and data visualization and wrote the 'Literature Review' and the 'Results' sections.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 218–233, 2024.
https://doi.org/10.1007/978-3-031-65238-7_15

The concept of the "15-minute city" emerges as a potent model for urban adaptation [2, 4]. It leverages the principles of chrono-urbanism to envision a city where basic functions are integrated into residential areas, encouraging active mobility and minimizing travel time to 15 min. Chrono-urbanism focuses on the spatio-temporal dimensions of urban planning, advocating for a distribution of functions that optimizes individuals' time usage, enabling a balance among utilitarian activities and leisure and social interactions. Moreover, by decreasing reliance on cars and improving access to urban functions, this time-centric perspective offers numerous benefits, including social inclusion, spatial justice, reduced energy consumption, noise, and air pollution,, and overall improvement in quality of life [4]. The proposed study investigates levels of compliance to the 15-minute city criteria across a metropolitan area. The aims include: i) understanding disparities among distinct parts of a metropolitan area in terms of access to SGIs; ii) comparing distinct modes of formalizing access to SGIs; iii) understanding the impact of urban form factors, such as enclosure, density, permeability, and centrality, on service access levels. Consequently, the study combines configurational analysis - using Space Syntax and Place Syntax metrics - spatial analysis, and statistical analysis to evaluate, investigate the dimensions of proximity, density, and diversity. The study contributes to the operationalization of the criteria central to developing urban regeneration strategies based on the 15-minute city concept. The analysis focuses on the Metropolitan City of Cagliari, Italy. It identifies urban environment factors, including density, permeability, centrality, enclosure, as areas of intervention for urban regeneration policies aimed at promoting the re-location of urban functions and, as a consequence, creating an urban environment conducive to inclusivity, local economic vitality, and active engagement in social, cultural, and economic activities. The article is structured into five sections: an introduction, a review of relevant literature on urban models focusing on proximity, density, and diversity in Sect. 2, a detailed description of the method in Sect. 3, an overview of analysis results in Sect. 4, and conclusions presenting the implications of the study's findings and their relevance to the ongoing discourse on urban reorganization.

2 Literature Review

The need to restructure urban spaces, infrastructures, and functions to improve quality of life, urban resilience, social inclusion, sustainability, and economic development is accentuated by the COVID-19 pandemic and the environmental crisis. The C40 cities initiative, representing 100 significant cities across multiple countries, underscores the importance of adopting the 15-minute city concept as pivotal for a sustainable and fair recovery from the pandemic. This perspective is adopted by numerous cities, including Milan, Paris, Bogotà, Portland, and Melbourne, and results in the implementation of strategies of urban regeneration aimed at promoting smart and sustainable mobility solutions, ecological infrastructure expansion, the redistribution of amenities and services, and creating multi-functional public spaces [5, 6].

The 15-minute city concept focuses on optimizing urban structures, land use, and services to encourage public transit and active mobility options, reducing travel times to services of general interest to just 15 min. This model is based on four criteria: density, diversity, proximity, and digitalization [2, 4]. Density refers to the ideal number

of residents sustaining a variety of services. Proximity focuses on the spatial closeness of SGIs, and integrates a spatial and temporal dimension. It implies the relocation of urban functions, the incentivization of active transportation and the transformation of public spaces. Diversity refers to the combination, at the district scale of distinct urban functions and the co-presence of distinct practices and identities. Lastly, digitalization involves utilizing Information and Communication Technology (ICT) solutions to optimize service provision. The restructuring of urban environment, based on these criteria, is conducive to encouraging active travel and social interactions, reducing emissions, improving resilience, and quality of life [7–16]. The 15-minute city concept builds upon the smart city paradigm, the concept of chrono-urbanism, and urban models developed to mitigate the adverse impacts of the modernist urban paradigm [1–3, 5, 17–21]. In its antecedents, the optimization of district size, access to public transit, active mobility, contiguity to natural and semi-natural areas, proximity to services, and diversity of functions are fundamental criteria outlined by the Neighbourhood Unit Concept (NUC) [22–25], New Urbanism [26–29], and transit-oriented development paradigms [29–32]. Density, diversity, and proximity to amenities are also identified as macro-scale built environment factors conducive to walkability [33–38]. Moreover, diversity, proximity, and density are fundamental components of urban vitality, defined as a social process resulting from the concentration, intensity, and diversity of activities activated by urban functions and form [39–42]. Various studies propose alternative measures of proximity, diversity, and density to evaluate environmental factors' influence on vitality, active travel, and access to urban functions. In particular, metrics for evaluating proximity, diversity, and density in the context of the 15-minute city criteria mainly focus on distance from points of interest, the number of destinations, and entropy measures [1, 3, 21, 43, 44]. The understanding and formalization of urban form factors are crucial for informing the development of urban regeneration strategies aiming to create inclusive, just, and resilient 15-minute cities.

3 Methodology

In order to investigate inequalities across the metropolitan city of Cagliari and compare distinct metrics of access to services of general interest, the proposed study combines spatial, statistical and configurational analysis. In particular, Place Syntax, Space Syntax and Network analysis tools are used to measure centrality of spaces and levels of access to SGIs.

3.1 Space Syntax

Space Syntax refers to a set of models and metrics aiming to understand the interdependence among social and spatial structures of built environments, or the spatial culture of societies. Space Syntax focuses on the configuration of spatial systems; configuration refers to the set of topological relations among elements interdependent in a spatial system. Topological relations determine systems of integration and segregation among spaces that manifest and reproduce the principle informing social practices and relations. In particular, the concept of movement economy formalizes the recursive, mutual

influences among spatial configuration, pedestrian movement and location of economic activities in an urban environment. It considers the influence of urban configuration on the distribution of pedestrian movement across spaces, demonstrating the concentration of people in most central/ integrated spaces. Consequently, the potential demand resulting from people's co-presence influences the location of economic activities. These, in turn, reinforce the concentration of people in central spaces and determines the need for adapting the urban spatial structure, by increasing its permeability. As a result, building on previous studies [3, 21], the proposed analysis uses integration metrics to investigate the spatial configuration of the area of interest. Integration measures the distance from each space to any potential destination in a spatial system. It measures a space's relevance as a destination. The definition of a radius isolates spatial sub-structures around an origin space enabling the measurement of configurational properties at micro-, meso-, and macro-scales. Moreover, measuring configurational properties at distinct scales is relevant to understanding the impact of spatial configuration on various modes of movement. In particular, radii ranging from 400 m to 3000 m are relevant for investigating the influence of spatial configuration on pedestrian movement [45].

3.2 Place Syntax Toolkit

The Place Syntax tool is an open-source spatial analysis platform that integrates Space Syntax models into urban environment analysis. It incorporates points of interest defined by spatial co-ordinates and quantitative data, and the spatial structure of an urban environment, defined by street segments, to measure conditions of access to local destinations. In particular, proximity to destination points is computed via the attraction distance (AD) and attraction reach (AR) metrics. AD measures the distance from the i-th origin point to the nearest destination point. AR measures conditions of access, from the i-th origin point, to a set of destination points. The AR metric for the i-th origin point and the k-th set of destinations, is computed as the sum of the complementary values of the distance from individual destinations divided by a predefined radius. As a result, the computation of proximity metrics is based on four input layers: a layer containing the origin points; a layer representing destinations, a segment map or an axial map representing the spatial structure of the area of interest, and a point layer representing apparent intersections among disconnected lines. The AR function addresses limitations of the conventional operationalization of proximity in terms of distance from the nearest destination by integrating a variety factor, formalized in terms of presence of alternative destinations for each service category and an impedance factor as a function of the distance of individual destinations from the origin point.

3.3 Organization of the Study

The study is articulated on five stages: i) selection and description of the area of interest; ii) computation of distinct metrics of access to SGIs and of a metropolitan scale indicator of spatial injustice; iii) computation of configurational and spatial metrics; iv) categorization of units of analysis and comparison of alternative categorizations; v) exploratory statistical analysis.

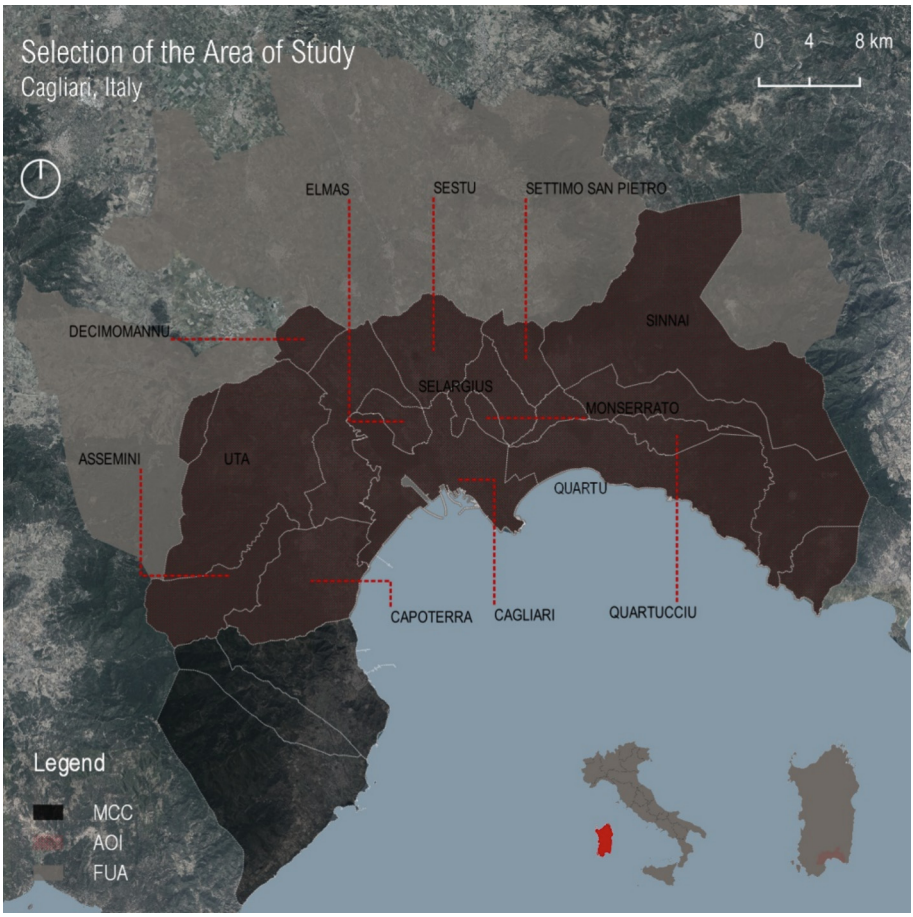


Fig. 1. Selection of the area of study (AOI): Muncipalities of the Metropolitan City of Cagliari (MCC) comprised into the Cagliari Functional Urban Area (FUA)

Selection and Description of the Area of Interest. The selected area of interest is the intersection among the functional area of Cagliari, as defined by the Urban Atlas service and the area of the Metropolitan City of Cagliari (Fig. 1).

Land cover units, including built areas, are selected as units of analysis. The spatial structure of the area of interest is described via a segment map derived from the road-centre line map retrieved from the Open Street Map service. The road-centre line map is edited by eliminating geometries related to spaces not suitable for pedestrian movement, labeled as Arterial, Trunk, bridleway, construction, cycleway, emergency, path, raceway, service, and track and is validated by repairing topological errors, via the Road Network Cleaner function of the Space Syntax Toolkit (SST). The sub-sequent step consists in the conversion of the revised road-centre line map into a segment map, via the Network Segmenter function of the SST. Lastly, the segment map is edited by eliminating sets of isolated segments. Local destinations are represented by amenities and services grouped

in eight categories: sustenance services, recreational activities, retail activities, Transportation services, education services, healthcare services, general public services and urban green areas.

Computation of Metrics of Access to SGIs. Levels of access to services are quantified in terms of alternative metrics, to compare distinct formalizations of conditions of access. Firstly, proximity is operationalized in terms of distance of the i-th origin point from the closest destination of the k-th category of services [1, 19, 43, 44, 46]. A second formalization of proximity consists in computing the number of Points of interest of the k-th category of services located in the service area of the i-th origin point. The service area refers to the set of spaces accessible on foot from the i-th origin point in a time frame inferior or equal to 15 min [17, 43, 47–49]. These metrics present specific limitations: the formalization of proximity in terms of distance from the nearest destinations disregards the dimension of individual preference and the importance in terms of quality of life, of the availability of multiple alternative destinations [3, 21, 50]. Vice versa, the operationalization of proximity in terms of the number of destinations in the service area of the unit of analysis, disregard the impedance factor represented by the distance of each destination from the origin point. As a consequence, the AR metric is used as a significant measure of access to a set of points of interest, since it integrates the impedance factor, relative to distances from the origin point of destinations, and the variety factor, relative to the presence of alternative destinations. The values of the indicators computed for each category of services are normalized via a range standardization function. Lastly, for each formalization of proximity, the metrics of access to individual categories of services are then aggregated into combined indicators of proximity (IPS_i). The Analytical Hierarchy Process is utilized to determine the relative importance of each metrics of access levels to a category of services (Table 1).

Computation of Configurational Metrics. Urban form is described in terms of meso-scale factors including permeability, centrality, density, enclosure. Permeability is measured via the Road Intersections density (DRI) metric. It is computed as the number of road intersections located at a distance, from the origin point, inferior or equal to 800 m. The value of 800 m is selected as the radius because it corresponds to a travel time inferior or equal to 15 min.

Centrality is measured in terms of angular integration at the local scale (radius equal to 800 m) and at the global scale (Radius equal to 40 km). Density is measured in terms of population density (DPOP). Lastly, enclosure is formalized in terms of average transversal dimension (W) of streets contiguous to the i-th unit of analysis and in terms of Openness (OPEN), computed as the average percentage of the edges of the j-th street segment, contiguous to the i-th unit of analysis, defined by continuous façades (Table 1).

Categorization of Units of Analysis. Distinct categorizations of the units of analysis are defined, based on the alternative metrics of access to services computed in stage 3. The units of analysis are divided into five categories defined by equal intervals of the values of the combined indicators of proximity. A measure of inter-cluster similarity, the Jaccard's Similarity Index, is then computed to investigate divergences among interpretations of the area of interest depending on alternative conceptualization of proximity. Lastly, metrics of spatial injustice are based on the distribution of the population among the modes of

Table 1. Description of selected indicators of access to services and of urban environment factors

Indicator	Description	Variable
INT_N	Topological Integration at radius n	Centrality
INT800	Topological Integration at radius 800 m	Centrality
CLUS	Clustering	Permeability
DEG_CEN	Degree Centrality	Centrality
OPEN	Openness of street fronts	Enclosure
W	Transversal dimension of urban spaces	Enclosure
DRI	Density of road intersections	Permeability
A_SER	Service Area surface	Permeability
DPOP	Density of population	Density
IPS_{AD}	Levels of proximity to SGI based on distance of i-th origin point from the closest destination for the k categories of services	Access to SGIs
IPS_{AR}	Levels of proximity to SGI based on distance and number of the n destinations, for the k categories of services, located at a distance inferior or equal to 800 m from the i-th origin point	Access to SGIs
IPS_{NUM}	Levels of proximity to SGI based on the number of destinations, for the k categories of services, located at a distance inferior or equal to 800 m from the i-th origin point	Access to SGIs

the combined indicators of Proximity. These metrics are computed as the proportion of urban population residing in units of analysis presenting modest and inadequate levels of access to services.

Statistical Analysis. Statistical analysis uses exploratory statistical analysis to investigate correlations among levels of access to services of general interest, under the alternative formalization of proximity, and meso-scale aspects of the urban environment, including permeability, density, enclosure and centrality. The observations are divided into ten quantiles, based on the values of the combined indices of proximity, and spatial units comprised in the first and last intervals are selected for exploratory statistical analysis: the analysis investigates the deviation among average values of the urban environment variables. The Average Chart function is used to measure the significance of the deviation of the mean value of the j-th variable for the i-th subset compared to the mean value calculated for the unselected observations. Significance is determined by the p-value derived from the f-statistic obtained from a regression incorporating a binary variable set to 1 for observations included in the i-th subset and 0 for the unselected observations.

4 Results

The evaluation of conditions of access to services of general interest (SGIs) underlines the polycentric structure of the Metropolitan City of Cagliari.

Urban cores and central areas, in fact, present levels of access to SGIs above the mean values observed in semi-central, suburban and marginal areas. In particular, a continuous spatial structure, including the ancient district of Marina and the zone of expansion of San Benedetto, emerges as the socio-economic and cultural center of the Metropolitan Area. Vice versa, areas of dispersed urbanization, present marginal access to SGIs and adequate levels of access to natural and semi-natural areas. Specific configurations can be observed related to each category of service. Regarding education services, optimal levels of access can be observed in central areas in Cagliari and Decimomannu, and in semi-central areas of the urban core of the city of Quartu Sant'Elena. Distinct clusters of observations presenting optinal levels of access to sustenance services can be observed in the central districts of Cagliari urban core. The central districts in Cagliari urban core also emerge as a metropolitan scale centrality, in terms of density of retail and recreational activities. Similar configurations emerge also regarding access to public general services

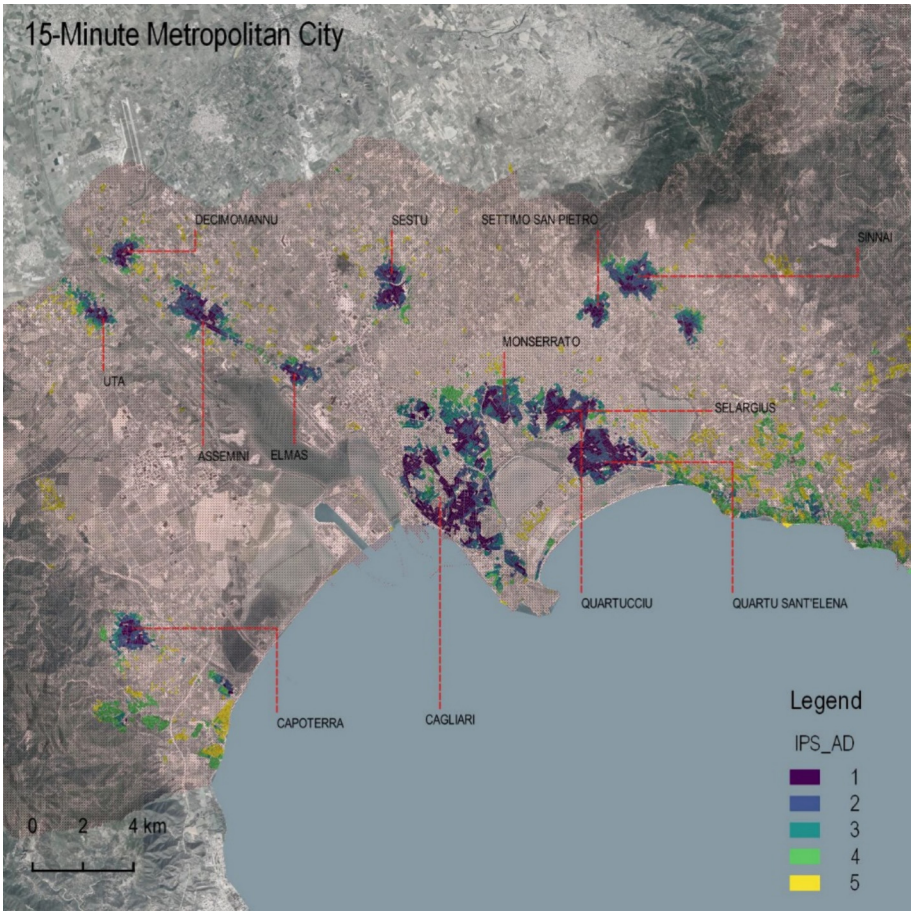


Fig. 2. Categories of observations derived from the metric IPS_{AD}, based on distance from the i-th observation of the nearest destination

and healthcare services. As a consequence, the spatial injustice metric is equal to 0.449, indicating that 44.92% of the total population of the units of analysis selected, equal to 171410 people, reside in areas presenting marginal access to SGI. Marginal access is indicated by values of the combined indicator of proximity, derived from AR metrics (IPS_{AR}), comprised in the last equal interval (values ranging from 0 to 0.15). Moreover, 18995 people (4.97% of the population of the units of analysis) reside in areas presenting values of the combined indicator IPS_{AR} comprised in the last quintile (values ranging from 0 to 0.018).

A spatial injustice metric, based on the formalization of proximity in terms of distance from the nearest destination, is equal to 0.041, indicating that 4.1% of the population, equal to 15612 people, resides in areas distant from services of General interest and presenting values of the combined indicator of proximity, derived from distance metrics IPS_{AD}, comprised in the last equal interval.

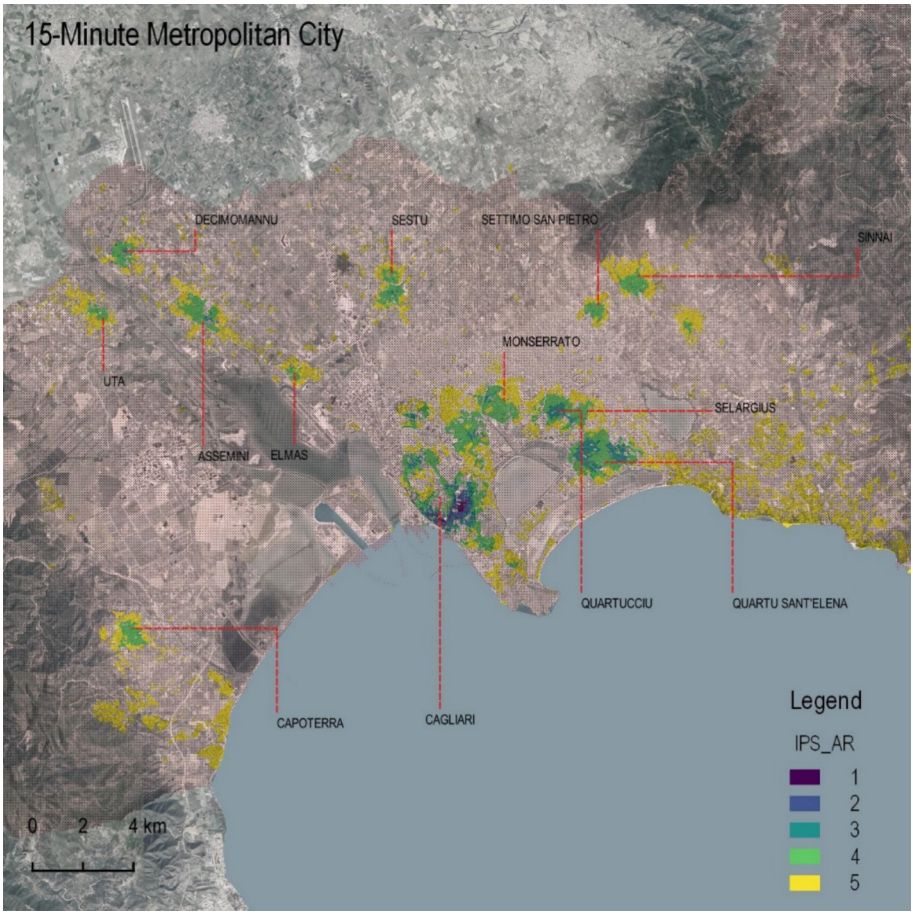


Fig. 3. Categories of observations derived from the IPS_{AR} metric, based on number of destinations in the service area of the i-th origin and of the distance from the i-th origin of the j-th destination

The comparison of metrics of access to services, based on alternative formalizations of proximity, underlines profound divergencies in the interpretation of the area of interest.

In particular, the similarity metric, computed for the first equal intervals of the indicators IPS_{AR} and IPS_{AD} is equal to 0.014, indicating that a modest percentage of observations, included in the union of the two sets, is included in the intersection among the two sets. More precisely, only 1.45% of observations comprised in the first equal interval of values of the IPS_{AD} indicator are included also in the first interval of values of the IPS_{AR} metric. Vice versa, A significant similarity, equal to 0.434, is observed among interval 1 of values of the Proximity indicator based on distance from the nearest destination and interval 4 of the proximity indicator based on AR metrics; it indicates that a significant proportion of observations categorized as areas presenting optimal levels of access to SGIs, based on mere distance from the nearest destination, are categorized as areas of modest services provision if considering distance from destinations and availability of multiple destinations.

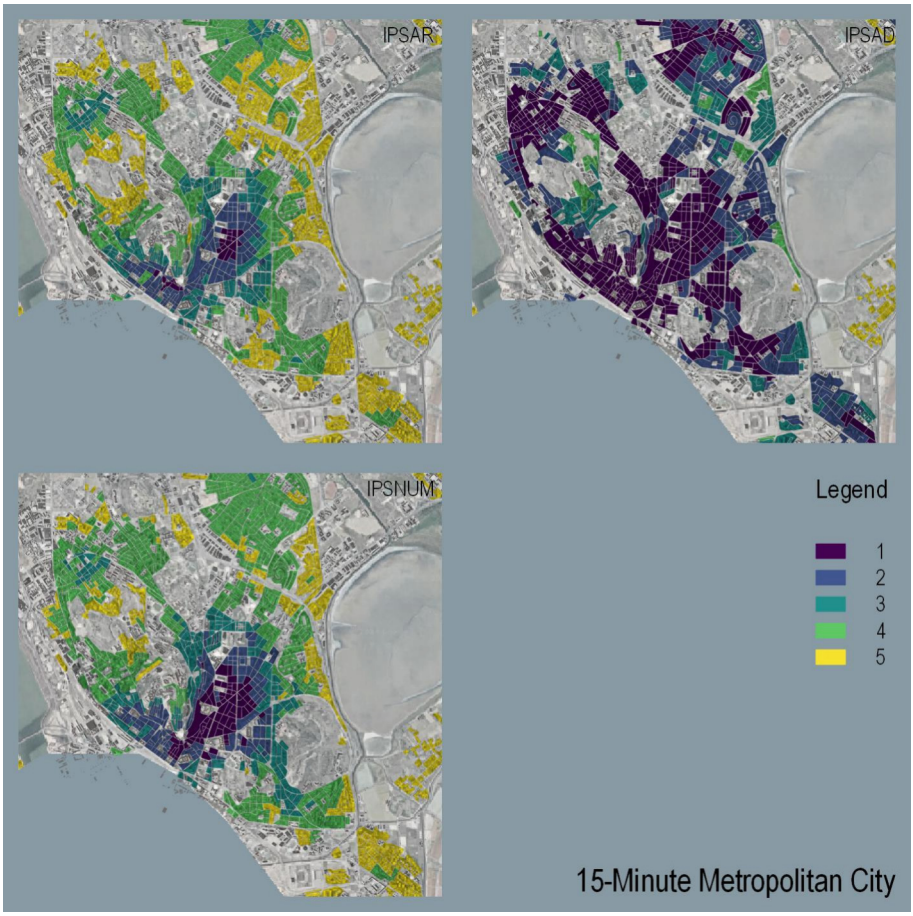


Fig. 4. Comparison of distinct metrics of Proximity in Cagliari Urban Core

Moderate similarity is observed among interval 1 of the values of the proximity metric based on the number of destinations in the service area of observations, IPSNUM, and interval 1 of the values of the indicator of proximity based on AR metrics, IPSAR. Superior similarity is observed among interval 1 of values of the IPSNUM indicator and interval 2 of the IPSAR indicator. Significant similarity is observed among sub-sets comprising observations that present modest and inadequate levels of access to services (Intervals 4 and 5 of values of the indicators IPSNUM and IPSAR. In particular 93.12% of observations categorized as areas presenting modest access to services, in terms of number of destinations in the service area of spatial units, are also identified as deprived areas in terms of AR metrics. The statistical analysis underlines that observations comprised in the first decile of values of the IPSAR metric presents a more compact, dense, enclosed, integrated and permeable structure. Mean values of metrics of local and global integration, road intersection density, degree centrality, service area surface, clustering, density are above the average values computed for unselected observations. Vice versa, mean openness and transversal dimension of urban spaces, inversely proportional to urban space enclosure, are inferior to the mean value computed for unselected observations. Analogous relations, among levels of access to services and urban environment variable, emerge when considering quantiles derived from values of Proximity metrics based on observations' distance from the closest destination.

Table 2. Statistical analysis of the sub-set of observations comprised in the first decile of values of the IPS_{AR} metric and of the IPS_{AD} metric

First Decile		IPS_{AR}		IPS_{AD}	
Metric	Parameter	Value	P-value	Value	P-value
INT_N	Average	0.0043	0.000	0.0043	0.000
	Deviation	0.0017	0.000	0.0015	0.000
INT800	Average	0.0006	0.000	0.0006	0.000
	Deviation	0.0006	0.000	0.0005	0.000
CLUS	Average	0.0304	0.000	0.0306	0.000
	Deviation	0.0248	0.000	0.0231	0.000
OPEN	Average	0.6558	0.000	0.6528	0.000
	Deviation	−0.1137	0.000	−0.0836	0.000
W	Average	28.0048	0.000	27.8059	0.000
	Deviation	−6.3889	0.000	−4.3983	0.000
DRI	Average	0.2566	0.000	0.2649	0.000
	Deviation	0.3769	0.000	0.2943	0.000
A_SER	Average	0.2740	0.000	0.2810	0.000
	Deviation	0.3259	0.000	0.2557	0.000
DPOP	Average	71.6100	0.000	73.3428	0.000
	Deviation	109.7290	0.000	92.3883	0.000

Vice versa, observations comprised in the last decile present a more segregated, coarse, dispersed urban structure. Mean values of the metrics global and local integration, Density of road intersections, density, service area surface are inferior to mean values computed for unselected observations. Enclosure, measured via the metrics openness and transversal dimension is above the mean values of unselected observations, similarly to observations presenting optimal levels of access to services. Analogous conditions are observed when considering spatial units comprised in the last decile of values of the IPS_{AD} metric.

Table 3. Statistical analysis of the sub-set of observations comprised in the last decile of values of the IPS_{AR} metric and of the IPS_{AD} metric

Last Decile		IPS_{AR}		IPS_{AD}	
Metric	Parameter	Value	P-value	Value	P-value
INT_N	Average	0.0047	0.0000	0.0047	0.000
	Deviation	−0.0030	0.0000	−0.0031	0.000
INT800	Average	0.0007	0.0000	0.0007	0.000
	Deviation	−0.0006	0.0000	−0.0006	0.000
CLUS	Average	0.0362	0.0000	0.0362	0.000
	Deviation	−0.0329	0.0000	−0.0329	0.000
OPEN	Average	0.6506	0.0000	0.6524	0.000
	Deviation	−0.0618	0.0000	−0.0796	0.000
W	Average	27.5649	0.0000	27.6637	0.000
	Deviation	−1.9865	0.0002	−2.9750	0.000
DRI	Average	0.3247	0.0000	0.3246	0.000
	Deviation	−0.3046	0.0000	−0.3037	0.000
A_SER	Average	0.3347	0.0000	0.3345	0.000
	Deviation	−0.2815	0.0000	−0.2798	0.000
DPOP	Average	90.5625	0.0000	90.6298	0.000
	Deviation	−79.9473	0.0000	−80.6203	0.000

The results' significance and implications are discussed in the subsequent sections.

5 Discussion and Conclusions

Several considerations emerge from the results. A first finding concerns the polycentric structure of the area of interest. It results from the co-presence of a metropolitan scale center, represented by the compact districts in Cagliari, and a structure of local centers comprising the compact cores of the municipalities of the Metropolitan City of Cagliari.

A second consideration concerns the conditions of spatial injustice determined by the concentration of services in central areas and the consequent significant proportion of the population residing in areas presenting modest conditions of density and diversity of services.

Moreover, the comparison of alternative formalizations of proximity and diversity underlines significant disparities among the results and the consequent interpretations of the area of interest. More precisely, intra-urban disparities, and the emergence of local and metropolitan-scale centers are better captured by metrics based on a conceptualization of proximity that considers both the impedance factor represented by the distance of the j-th destination from the i-th observation and the plurality factor represented by the presence of multiple alternative destinations close to the i-th observation.

As a result, metrics based on formalizations of proximity as the number of destinations in the served area of the i-th observation and as the distance from the i-the observation of the nearest destination disregard significant components of proximity, respectively the impedance factor represented by distance and individuals' preference for multiple alternative destinations. Lastly, statistical analyses reveal a relation among proximity and configurational factors of the urban environment. More precisely, compact, integrated, permeable and dense spatial structure are a distinctive element of areas presenting optimal levels of access to services. As a result, compactness, density, centrality and permeability emerges as conditions conducive to the location of economic activities and, consequently, to density and diversity of SGIs.

The relevance of the proposed study lies in distinct aspects: firstly, the study underlines the conditions of spatial injustice, in terms of disparities in conditions of access to services of general interest, persisting in urbanized areas. Secondly, the study underlines the emergence of the consolidated, compact cores as centralities of the metropolitan structure, and the permanence of the compact city as a pole of density and diversity of urban functions. Moreover, the study demonstrates the co-presence, in the contemporary city, of 15-minute districts and of mono-functional areas, thus underlining the need to realize the 15-minute city concept starting from the reorganization of sub-urban areas and of areas of dispersed urbanization. In particular, the significant relation among conditions of density and diversity of services and specific meso- and macro-scale configurational properties of the built environment suggests the relevance of strategies of densification, grid intensification, regeneration and completion of areas contiguous to the compact, consolidated parts of the urban structure as actions for creating conditions conducive to the relocation of urban functions, the improvement of access to fundamental services and the consequent promotion of social inclusion. Lastly, the study underlines the impact of alternative conceptualizations and operationalization of the criteria of proximity and diversity on the interpretation of the urban environment organization and its conditions of social and spatial injustice. Consequently, the study demonstrates the importance of considering the limits of conventional formalizations of proximity for developing metrics for evaluating advantages, constraints and criticalities of the urban environment. The future development of the study will focus on the use of spatial and linear regression models for a detailed investigation of the relation among distribution of urban functions and the configuration of the urban environment. The aim is to develop analytic procedures, incorporating configurational, spatial, and statistical analysis, for understanding

the conditions of urban quality and spatial injustice, and enabling informed decisions in the context of the definition of urban adaptation and regeneration policies amidst the post-pandemic scenario and climate alterations.

Disclosure of Interests. The authors have no competing interests.

References

1. Logan, T.M., Hobbs, M.H., Conrow, L.C., Reid, N.L., Young, R.A., Anderson, M.J.: The x-minute city: Measuring the 10, 15, 20-minute city and an evaluation of its use for sustainable urban design. Cities **131**, 103924 (2022). https://doi.org/10.1016/j.cities.2022.103924
2. Allam, Z., Bibri, S.E., Chabaud, D., Moreno, C.: The '15-Minute City' concept can shape a net-zero urban future. Humanities Soc. Sci. Commun. **9**, 126 (2022). https://doi.org/10.1057/s41599-022-01145-0
3. Murgante, B., Patimisco, L., Annunziata, A.: Developing a 15-minute city: a comparative study of four Italian Cities-Cagliari, Perugia, Pisa, and Trieste. Cities **146**, 104765 (2024). https://doi.org/10.1016/j.cities.2023.104765
4. Moreno, C., Allam, Z., Chabaud, D., Gall, C., Pratlong, F.: Introducing the "15-Minute City": sustainability, resilience and place identity in future post-pandemic cities. Smart Cities. **4**, 93–111 (2021). https://doi.org/10.3390/smartcities4010006
5. C40 Cities Climate Leadership Group: How to build back better with a 15-minute city (2020). https://www.c40knowledgehub.org/s/article/How-to-build-back-better-with-a-15-minute-city
6. Miller, D.: Mayors engaging with the G20: make COVID-19 recovery green and just to deliver a successful COP26 (2021). https://www.c40.org/news/mayors-engaging-with-the-g20-make-covid-19-recovery-green-and-just/
7. Frank, L.D., Sallis, J.F., Conway, T.L., Chapman, J.E., Saelens, B.E., Bachman, W.: Many pathways from land use to health: associations between neighborhood walkability and active transportation, body mass index, and air quality. J. Am. Plann. Assoc. **72**, 75–87 (2006). https://doi.org/10.1080/01944360608976725
8. Kamble, T., Bahadure, S.: Investigating application of compact urban form in central Indian cities. Land Use Policy **109**, 105694 (2021). https://doi.org/10.1016/j.landusepol.2021.105694
9. Kesarovski, T., Hernández-Palacio, F.: Time, the other dimension of urban form: measuring the relationship between urban density and accessibility to grocery shops in the 10-minute city. Environ. Plann. B: Urban Anal. City Sci. **50**, 44–59 (2023). https://doi.org/10.1177/23998083221103259
10. Lang, W., Chen, T., Chan, E.H.W., Yung, E.H.K., Lee, T.C.F.: Understanding livable dense urban form for shaping the landscape of community facilities in Hong Kong using fine-scale measurements. Cities **84**, 34–45 (2019). https://doi.org/10.1016/j.cities.2018.07.003
11. Lang, W., Lang, H., Hui, E.C.M., Chen, T., Wu, J., Jahre, M.: Measuring urban vibrancy of neighborhood performance using social media data in Oslo. Norway. Cities. **131**, 103908 (2022). https://doi.org/10.1016/j.cities.2022.103908
12. Ewing, R., Cervero, R.: Travel and the Built Environment. J. Am. Plann. Assoc. **76**, 265–294 (2010). https://doi.org/10.1080/01944361003766766
13. Kim, S.: Urban vitality, urban form, and land use: their relations within a geographical boundary for walkers. Sustainability. **12** (2020). https://doi.org/10.3390/su122410633
14. Kourtit, K., Nijkamp, P., Wahlström, M.H.: How to make cities the home of people – a 'soul and body' analysis of urban attractiveness. Land Use Policy **111**, 104734 (2021). https://doi.org/10.1016/j.landusepol.2020.104734

15. Mouratidis, K., Yiannakou, A.: What makes cities livable? Determinants of neighborhood satisfaction and neighborhood happiness in different contexts. Land Use Policy **112**, 105855 (2022). https://doi.org/10.1016/j.landusepol.2021.105855
16. Mouratidis, K., Yiannakou, A.: COVID-19 and urban planning: Built environment, health, and well-being in Greek cities before and during the pandemic. Cities **121**, 103491 (2022). https://doi.org/10.1016/j.cities.2021.103491
17. Abdelfattah, L., Deponte, D., Fossa, G.: The 15-minute city: interpreting the model to bring out urban resiliencies. Transp. Res. Procedia. **60**, 330–337 (2022). https://doi.org/10.1016/j.trpro.2021.12.043
18. Di Marino, M., Tomaz, E., Henriques, C., Chavoshi, S.H.: The 15-minute city concept and new working spaces: a planning perspective from Oslo and Lisbon. Eur. Plan. Stud. **31**, 598–620 (2023). https://doi.org/10.1080/09654313.2022.2082837
19. Ferrer-Ortiz, C., Marquet, O., Mojica, L., Vich, G.: Barcelona under the 15-Minute City Lens: mapping the accessibility and proximity potential based on pedestrian travel times. Smart Cities. **5**, 146–161 (2022). https://doi.org/10.3390/smartcities5010010
20. Kissfazekas, K.: Circle of paradigms? Or '15-minute' neighbourhoods from the 1950s. Cities **123**, 103587 (2022). https://doi.org/10.1016/j.cities.2022.103587
21. Murgante, B., Valluzzi, R., Annunziata, A.: Developing a 15-minute city: evaluating urban quality using configurational analysis. The case study of Terni and Matera, Italy. Applied Geography **162**, 103171 (2024). https://doi.org/10.1016/j.apgeog.2023.103171
22. Mann, P.H.: The socially balanced neighbourhood unit. Town Plann. Rev. **29**, 91–98 (1958)
23. Patricios, N.N.: Urban design principles of the original neighbourhood concepts. jum. 6, 21–32 (2001). https://doi.org/10.51347/jum.v6i1.3900
24. Talen, E.: Social science and the planned neighbourhood. Town Plann. Rev. **88**, 349–372 (2017). https://doi.org/10.3828/tpr.2017.22
25. Perry, C.: The neighborhood unit. In: The city reader, pp. 607–619. Routledge (2015)
26. Congress for the New Urbanism: The Charter of the New Urbanism (2000). https://www.cnu.org/who-we-are/charter-new-urbanism
27. Ellis, C.: The new Urbanism: critiques and rebuttals. J. Urban Des. **7**, 261–291 (2002). https://doi.org/10.1080/1357480022000039330
28. Katz, P.: The New Urbanism: Toward an Architecture of Community. McGraw-Hill, Incorporated, New York, United States (1994)
29. Newman, P.W., Kenworthy, J.R.: The land use—transport connection: an overview. Land Use Policy **13**, 1–22 (1996). https://doi.org/10.1016/0264-8377(95)00027-5
30. Ibraeva, A., Correia, G.H. de A., Silva, C., Antunes, A.P.: Transit-oriented development: A review of research achievements and challenges. Transp. Res. Part A: Policy Practice. **132**, 110–130 (2020). https://doi.org/10.1016/j.tra.2019.10.018
31. Calthorpe, P.: The Next American Metropolis. Ecology, Community and the American Dream. Princeton Architectural Press, New York, United States (1993)
32. Cervero, R., Radisch, C.: Travel choices in pedestrian versus automobile oriented neighborhoods. Transp. Policy **3**, 127–141 (1996). https://doi.org/10.1016/0967-070X(96)00016-9
33. Cervero, R., Kockelman, K.: Travel demand and the 3Ds: Density, diversity, and design. Transp. Res. Part D: Transp. Environ. **2**, 199–219 (1997). https://doi.org/10.1016/S1361-9209(97)00009-6
34. Lee, C., Moudon, A.V.: The 3Ds+R: Quantifying land use and urban form correlates of walking. Transp. Res. Part D: Transp. Environ. **11**, 204–215 (2006). https://doi.org/10.1016/j.trd.2006.02.003
35. Hall, C.M., Ram, Y.: Walk score® and its potential contribution to the study of active transport and walkability: a critical and systematic review. Transp. Res. Part D: Transp. Environ. **61**, 310–324 (2018). https://doi.org/10.1016/j.trd.2017.12.018

36. Pikora, T.J., Bull, F.C.L., Jamrozik, K., Knuiman, M., Giles-Corti, B., Donovan, R.J.: Developing a reliable audit instrument to measure the physical environment for physical activity. Am. J. Prev. Med. **23**, 187–194 (2002). https://doi.org/10.1016/S0749-3797(02)00498-1
37. Pikora, T.J., Giles-Corti, B., Knuiman, M.W., Bull, F.C., Jamrozik, K., Donovan, R.J.: Neighborhood environmental factors correlated with walking near home: Using SPACES. Med. Sci. Sports Exerc. **38**, 708–714 (2006). https://doi.org/10.1249/01.mss.0000210189.64458.f3
38. Clifton, K.J., Livi Smith, A.D., Rodriguez, D.: The development and testing of an audit for the pedestrian environment. Landsc. Urban Plan. **80**, 95–110 (2007). https://doi.org/10.1016/j.landurbplan.2006.06.008
39. Garau, C., Annunziata, A.: A method for assessing the vitality potential of urban areas. The case study of the Metropolitan City of Cagliari, Italy. City, Territory and Architecture. 9, 7 (2022). https://doi.org/10.1186/s40410-022-00153-6
40. Mouratidis, K., Poortinga, W.: Built environment, urban vitality and social cohesion: Do vibrant neighborhoods foster strong communities? Landsc. Urban Plan. **204**, 103951 (2020). https://doi.org/10.1016/j.landurbplan.2020.103951
41. Montgomery, J.: Making a city: Urbanity, vitality and urban design. Null. **3**, 93–116 (1998). https://doi.org/10.1080/13574809808724418
42. Zumelzu, A., Barrientos-Trinanes, M.: Analysis of the effects of urban form on neighborhood vitality: five cases in Valdivia, Southern Chile. J. Housing Built Environ. **34**, 897–925 (2019). https://doi.org/10.1007/s10901-019-09694-8
43. Capasso Da Silva, D., King, D.A., Lemar, S.: Accessibility in practice: 20-Minute city as a sustainability planning goal. Sustainability. **12** (2020). https://doi.org/10.3390/su12010129
44. Gaglione, F., Gargiulo, C., Zucaro, F., Cottrill, C.: Urban accessibility in a 15-minute city: a measure in the city of Naples. Italy. Transp. Res. Procedia. **60**, 378–385 (2022). https://doi.org/10.1016/j.trpro.2021.12.049
45. Dhanani, A., Tarkhanyan, L., Vaughan, L.: Estimating pedestrian demand for active transport evaluation and planning. Transp. Res. Part A: Policy Practice. **103**, 54–69 (2017). https://doi.org/10.1016/j.tra.2017.05.020
46. Willberg, E., Fink, C., Toivonen, T.: The 15-minute city for all? – measuring individual and temporal variations in walking accessibility. J. Transp. Geogr. **106**, 103521 (2023). https://doi.org/10.1016/j.jtrangeo.2022.103521
47. Burke, J., Gras Alomà, R., Yu, F., Kruguer, J.: Geospatial analysis framework for evaluating urban design typologies in relation with the 15-minute city standards. J. Bus. Res. **151**, 651–667 (2022). https://doi.org/10.1016/j.jbusres.2022.06.024
48. Hosford, K., Beairsto, J., Winters, M.: Is the 15-minute city within reach? evaluating walking and cycling accessibility to grocery stores in Vancouver. Transp. Res. Interdisciplinary Perspectives. **14**, 100602 (2022). https://doi.org/10.1016/j.trip.2022.100602
49. Papadopoulos, E., Sdoukopoulos, A., Politis, I.: Measuring compliance with the 15-minute city concept: State-of-the-art, major components and further requirements. Sustain. Cities Soc. **99**, 104875 (2023). https://doi.org/10.1016/j.scs.2023.104875
50. Blečić, I., Cecchini, A., Congiu, T., Fancello, G., Trunfio, G.A.: Evaluating walkability: a capability-wise planning and design support system. Int. J. Geogr. Inf. Sci. **29**, 1350–1374 (2015). https://doi.org/10.1080/13658816.2015.1026824

Computational Methods for Porous Geomaterials (CompPor 2024)

Numerical Modeling of Fluid-Saturated Porous Sample Loading Based on Thermodynamically Compatible System Theory

Mikhail Novikov[1,2(✉)], Vadim Lisitsa[1], and Evgeniy Romenski[2]

[1] Trofimuk Institute of Petroleum Geology and Geophysics SB RAS, Novosibirsk 630090, Russia
novikovma@ipgg.sbras.ru
[2] Sobolev Institute of Mathematics SB RAS, Novosibirsk 630090, Russia
evrom@math.nsc.ru

Abstract. A quasi-static approximation of a thermodynamically compatible system of PDEs is presented to model the loading test for a two-phase (solid-fluid) sample. To numerically solve the resulting PDEs written in terms of displacements, we use a second-order finite-difference scheme on a staggered grid. Numerical results demonstrate the application of the presented approach to estimate seismic attenuation in two-phase media on different scales, involving an effective porosity model of fractured media on the mesoscale or the geometry of a single pore directly at the microscale.

Keywords: Numerical rock physics · Thermodynamically compatible systems · Poroelasticity · Quasistatic modeling · Finite differences

1 Introduction

The last decades of studying the non-elastic behavior of fluid-saturated rocks demonstrated that seismic attributes allow for the identification of the internal structure of heterogeneous formations and fluid mobility within them. These studies have potential applications in fractured reservoir monitoring for different purposes: oil recovery enhancement, carbon dioxide sequestration, and thermal energy production. As the fractured rock usually has a multiscale structure, several phenomena causing nonelastic behavior occur. In particular, in the presence of fluid within a heterogeneous porous rock, fluid flows occur both between heterogeneities (for example, fractures) and between pores. The first type mentioned is called wave-induced fluid flow (WIFF), which affects the velocity and attenuation of propagating seismic waves widely in the seismoacoustic frequency range [1]. WIFF intensity depends on the physical properties contrast between host

This work was supported by the Russian Science Foundation grant no. 19-77-20004.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 237–249, 2024.
https://doi.org/10.1007/978-3-031-65238-7_16

rock and heterogeneities and also their connectivity in the considered domain. Second, microscale phenomena is called squirt-flow [2]. It depends mostly on the fluid properties and explicit geometry of a single pore in the medium. Thus, modeling mesoscale fluid flows such as WIFF requires a fairly large computational domain (compared to the pore size) in terms of representativeness of the heterogeneous structure, and a two-phase medium (solid + liquid) can only be effectively described if both phases are present at every point on the continuum. In contrast, considering a single pore when modeling its geometry can only be done with explicit phase division. As a result, it is impossible to properly take into account fluid flow processes on different scales in one modeling cycle, and if the effective mathematical model of two-phase media has some limitations on one phase transition, one cannot apply only one model to investigate fluid flow at all scales. While the first problem is usually caused by overwhelming computational costs, the second one seems more solvable by introducing the universal model to describe two-phase media, including single-phase limits.

One of the actively developing approaches nowadays is based on the theory of Symmetric Hyperbolic Thermodynamically Compatible (SHTC) systems of conservation laws [3,4]. This theory is a powerful tool for developing new mathematically well-posed models whose governing equations satisfy the laws of irreversible thermodynamics. Our studies are based on SHTC models of porous media, considered as a two-phase mixture of solid and liquid, presented in [5–8]. One of the main advantages of the SHTC porous media model is that it describes the behavior of the medium for the entire porosity range from 0 to 1. It also allows the diffuse interface approach to be used for modeling in regions with interfaces between media with different porosities, including pure fluid and pure elastic media.

The rest of the paper is organized as follows. Section 2 briefly describes the linear SHTC governing equations for wave propagation in a saturated porous medium and their transformed form, which is then used to model quasistatic loading. In Sect. 3, we present a finite-difference approximation of the quasi-static equations and approximate the boundary conditions that close the resulting system of equations. In Sect. 4, we consider numerical modeling of the uniaxial loading of a synthetic fractured rock sample to validate the presented method. The results of these experiments are demonstrated and described in Sect. 5. Finally, in the conclusion, we summarize the presented algorithm and discuss its possible applications.

2 Quasi-Static Approximation for Poroelastic Model

In our work, we consider a 2D system of equations governing small-amplitude wave propagation in an elastic porous fluid-saturated medium:

$$\begin{gathered}
\rho \frac{\partial v^i}{\partial t} + \frac{\partial p}{\partial x_i} - \frac{\partial s_{ik}}{\partial x_k} = 0, \\
\frac{\partial q^k}{\partial t} + \left(\frac{1}{\rho_1} - \frac{1}{\rho_2} \right) \frac{\partial p}{\partial x_k} = -\frac{c_1 c_2}{\theta} q^k, \\
\frac{\partial p}{\partial t} + K \frac{\partial v^k}{\partial x_k} + \frac{\alpha_1 \alpha_2}{\rho} \left(\rho_2 - \rho_1 \right) K \frac{\partial q^k}{\partial x_k} = 0, \\
\frac{\partial s_{ik}}{\partial t} - \mu \left(\frac{\partial v^i}{\partial x_k} + \frac{\partial v^k}{\partial x_i} - \frac{2}{3} \delta_{ik} \frac{\partial v^j}{\partial x_j} \right) = -\frac{s_{ik}}{\tau}.
\end{gathered} \tag{1}$$

Here, we use Einstein notation to represent summation. The system (1) describes two vector fields of fluid-solid mixture velocity $\vec{v} = (v^1\ v^2)^T$ and relative fluid velocity $\vec{q} = (q^1\ q^2)^T$, scalar field of fluid pressure p and a tensor field of deviatoric stress

$$\boldsymbol{s} = \begin{pmatrix} s_{11} & s_{12} \\ s_{12} & s_{22} \end{pmatrix}. \tag{2}$$

Note that it is convenient here to consider the deviatoric part of the stress tensor, and to recover the full stress tensor $\boldsymbol{\sigma}$ one should combine $\boldsymbol{s}$ with fluid pressure [5]. The coefficients of Eqs. (1) include the material properties of both phases. We refer lower indices for material constants 1 and 2 corresponding to fluid and solid phases, consequently. Here α_1 and α_2 are volume fractions of fluid and solid phases (α_1 is porosity and $\alpha_2 = 1 - \alpha_1$); ρ, ρ_1 and ρ_2 are mixture, fluid and solid densities; $c_i = \alpha_i \rho_i / \rho$ ($i \in 1, 2$) are mass fractions of the phases. The effective elastic properties of a mixture are defined by the bulk modulus K and shear modulus μ. Note that as we consider a two-phase mixture of solid and inviscid fluid, these moduli are connected with single-phase moduli as follows:

$$K = \left(\frac{\alpha_1}{K_1} + \frac{\alpha_2}{K_2} \right)^{-1}, \quad \mu = \alpha_2 \mu_2. \tag{3}$$

Finally, θ and τ represent the interfacial friction coefficient and relaxation time [8]. In our work, we consider the limit case $\tau \to \infty$, so the right-side term of the fourth equation in (1) vanishes.

A popular approach to investigate the fluid flow within a heterogeneous poroelastic medium is a quasi-static modeling, as it allows one to consider the representative volume of the medium under loading at a wide range of frequencies without any domain expansion due to satisfy the typical scale of the process, defined by the wavelength. To observe fluid motion distribution, it is convenient to apply the quasi-static approximation because dynamic modeling results in high wave scattering at high frequencies [9]. We convert the system (1) into a quasi-static formulation with mixture displacement $\vec{u} = (u^1\ u^2)^T$ and relative fluid displacement $\vec{w} = (w^1\ w^2)^T$. To do so, we neglect the acceleration terms and reformulate the system in displacement-stress form. As a result, we obtain the system

$$\begin{gathered} \frac{\partial p}{\partial x_i} - \frac{\partial \sigma_{ik}}{\partial x_k} = 0, \\ \left(\frac{1}{\rho_1} - \frac{1}{\rho_2} \right) \frac{\partial p}{\partial x_k} = -\frac{c_1 c_2}{\theta} \frac{\partial w^k}{\partial t}, \\ \frac{\partial p}{\partial t} + K \frac{\partial^2 u^k}{\partial t \partial x_k} + \frac{\alpha_1 \alpha_2}{\rho} (\rho_2 - \rho_1) K \frac{\partial^2 w^k}{\partial t \partial x_k} = 0, \\ \frac{\partial s_{ik}}{\partial t} - \mu \left(\frac{\partial^2 u^i}{\partial t \partial x_k} + \frac{\partial u^k}{\partial t \partial x_i} - \frac{2}{3} \delta_{ik} \frac{\partial^2 u^j}{\partial t \partial x_j} \right) = 0. \end{gathered} \tag{4}$$

After this, we perform the Fourier transform to neglect the time derivatives and obtain

$$\begin{gathered}\frac{\partial p}{\partial x_i}-\frac{\partial s_{ik}}{\partial x_k}=0,\\ \left(\frac{1}{\rho_1}-\frac{1}{\rho_2}\right)\frac{\partial p}{\partial x_k}=-i\frac{c_1c_2}{\theta}\omega w^k,\\ p+K\frac{\partial u^k}{\partial x_k}+\frac{\alpha_1\alpha_2}{\rho}\left(\rho_2-\rho_1\right)K\frac{\partial w^k}{\partial x_k}=0,\\ s_{ik}-\mu\left(\frac{\partial u^i}{\partial x_k}+\frac{\partial u^k}{\partial x_i}-\frac{2}{3}\delta_{ik}\frac{\partial u^j}{\partial x_j}\right)=0,\end{gathered}\tag{5}$$

where ω is the frequency. Substituting the fluid pressure and stress component expressions from the third and fourth equations into the first and second equations in (5), we can obtain a closed second-order PDE system on displacements:

$$\begin{gathered}\frac{\partial}{\partial x_i}\left[K\frac{\partial u^k}{\partial x_k}+N\frac{\partial w^k}{\partial x_k}\right]+\frac{\partial}{\partial x_k}\left[\mu\left(\frac{\partial u^i}{\partial x_k}+\frac{\partial u^k}{\partial x_i}-\frac{2}{3}\delta_{ik}\frac{\partial u^j}{\partial x_j}\right)\right]=0,\\ \frac{\partial}{\partial x_j}\left[K\frac{\partial u^k}{\partial x_k}+N\frac{\partial w^k}{\partial x_k}\right]=iL\omega w^j.\end{gathered}\tag{6}$$

In component-wise form, this system reads as

$$\begin{gathered}\frac{\partial}{\partial x_1}\left[\left(K+\frac{4}{3}\mu\right)\frac{\partial u^1}{\partial x_1}+\left(K-\frac{2}{3}\mu\right)\frac{\partial u^2}{\partial x_2}+N\left(\frac{\partial w^1}{\partial x_1}+\frac{\partial w^2}{\partial x_2}\right)\right]\\ +\frac{\partial}{\partial x_2}\left[\mu\left(\frac{\partial u^1}{\partial x_2}+\frac{\partial u^2}{\partial x_1}\right)\right]=0,\\ \frac{\partial}{\partial x_2}\left[\left(K-\frac{2}{3}\mu\right)\frac{\partial u^1}{\partial x_1}+\left(K+\frac{4}{3}\mu\right)\frac{\partial u^2}{\partial x_2}+N\left(\frac{\partial w^1}{\partial x_1}+\frac{\partial w^2}{\partial x_2}\right)\right]\\ +\frac{\partial}{\partial x_1}\left[\mu\left(\frac{\partial u^1}{\partial x_2}+\frac{\partial u^2}{\partial x_1}\right)\right]=0,\\ \frac{\partial}{\partial x_1}\left[K\left(\frac{\partial u^1}{\partial x_1}+\frac{\partial u^2}{\partial x_2}\right)+N\left(\frac{\partial w^1}{\partial x_1}+\frac{\partial w^2}{\partial x_2}\right)\right]=iL\omega w^1,\\ \frac{\partial}{\partial x_2}\left[K\left(\frac{\partial u^1}{\partial x_1}+\frac{\partial u^2}{\partial x_2}\right)+N\left(\frac{\partial w^1}{\partial x_1}+\frac{\partial w^2}{\partial x_2}\right)\right]=iL\omega w^2.\end{gathered}\tag{7}$$

For simplicity, here we denote

$$\begin{gathered}N=\frac{\alpha_1\alpha_2}{\rho}K(\rho_2-\rho_1),\\ L=\frac{c_1c_2}{\theta}\left(\frac{1}{\rho_1}-\frac{1}{\rho_2}\right)^{-1}.\end{gathered}\tag{8}$$

System (7) allows us to obtain displacements first and then recover pressure and stress components using the last two equations from (5). To set a boundary value problem in a limited domain Ω with boundary $\partial\Omega$ boundary conditions should be defined. In our case, we define the normal stress and restrict the fluid displacement at the boundary:

$$\begin{gathered}\boldsymbol{\sigma}\cdot\vec{n}|_{\partial\Omega}=\vec{\phi}(\vec{x}),\\ \mathbf{w}\cdot\vec{n}|_{\partial\Omega}=0.\end{gathered}\tag{9}$$

Here $\vec{n}$ is the external normal vector to the boundary, and $\vec{\phi}(\vec{x})$ is a smooth enough function defined at the boundary ($\vec{x}\in\partial\Omega$). In particular, further we will be considering the rectangular domain $\Omega=\{\vec{x}:x_1\in[x_{10},x_{11}],\ x_2\in[x_{20},x_{21}]\}$ (Fig. 1, left). In this case, the boundary $\partial\Omega$ consists of straight line segments

aligned parallel to axes. For example, for the left and right sides of the rectangle boundary $\partial\Omega_L = \{x : x_1 \in [x_{10}, x_{11}],\ x_2 = x_{11}\}$ and $\partial\Omega_R = \{x : x_1 \in [x_{10}, x_{11}],\ x_2 = x_{21}\}$ the component-wise form of the boundary conditions with the use of third and fourth equations of (5) gives

$$\begin{gathered} \sigma_{11} = \left(K + \tfrac{4}{3}\mu\right)\frac{\partial u^1}{\partial x_1} + \left(K - \tfrac{2}{3}\mu\right)\frac{\partial u^2}{\partial x_2} + N\left(\frac{\partial w^1}{\partial x_1} + \frac{\partial w^2}{\partial x_2}\right) = \phi_{11}, \\ \sigma_{13} = \mu\left(\frac{\partial u^1}{\partial x_2} + \frac{\partial u^2}{\partial x_1}\right) = \phi_{13}, \\ w_1 = 0. \end{gathered} \tag{10}$$

Similarly, for the rest of the boundary, we assume boundary conditions on σ_{33}, σ_{13}, and ω_3:

$$\begin{gathered} \sigma_{33} = \left(K - \tfrac{4}{3}\mu\right)\frac{\partial u^1}{\partial x_1} + \left(K + \tfrac{2}{3}\mu\right)\frac{\partial u^2}{\partial x_2} + N\left(\frac{\partial w^1}{\partial x_1} + \frac{\partial w^2}{\partial x_2}\right) = \phi_{33}, \\ \sigma_{13} = \mu\left(\frac{\partial u^1}{\partial x_2} + \frac{\partial u^2}{\partial x_1}\right) = \phi_{13}, \\ w_3 = 0. \end{gathered} \tag{11}$$

3 Numerical Method

Numerical solution of Eqs. (7) within a rectangular domain $\Omega = [x_{10}, x_{11}] \times [x_{20}, x_{21}]$ implies finite differences approximating the derivatives on a staggered grid (Fig. 1), resulting in a second-order finite-difference scheme. The computational domain is presented by a regular rectangular grid with grid steps Δx_1 and Δx_2 in axes directions. The grid contains nodes where different variables are defined and different equations are stated. From now on, $i,\ j \in \mathbb{Z}$. First node group with indices $(i, j + 1/2)$ $(i = \overline{1, N_1 - 1},\ j = \overline{0, N_2 - 1})$, or with node coordinates $\vec{x} = ((i - 1/2)\Delta x_1, j\Delta x_2)$, store displacement components u^1, w^1 and second derivatives of these components. Second components of displacement vectors u^2, w^2 with their second derivatives are defined at node group with indices $(i + 1/2, j)$ and coordinates $(i\Delta x_1, (j - 1)\Delta x_2)$ $(i = \overline{0, N_1 - 1},\ j = \overline{1, N_2 - 1})$. Finally, we define material properties by the constants presented above in nodes with indices $(i + 1/2, j + 1/2)$ and coordinates $(i\Delta x_1, j\Delta x_2)$ $(i = \overline{0, N_1 - 1},\ j = \overline{0, N_2 - 1})$. First derivatives are approximated by second-order central differences:

$$\begin{aligned}
&\frac{\left(K+\frac{4}{3}\mu\right)_{i+1/2,j+1/2}D_1[u^1]_{i+1/2,j+1/2}-\left(K+\frac{4}{3}\mu\right)_{i-1/2,j+1/2}D_1[u^1]_{i-1/2,j+1/2}}{\Delta x_1}\\
&+\frac{\left(K-\frac{2}{3}\mu\right)_{i+1/2,j+1/2}D_2[u^2]_{i+1/2,j+1/2}-\left(K-\frac{2}{3}\mu\right)_{i-1/2,j+1/2}D_2[u^2]_{i-1/2,j+1/2}}{\Delta x_1}\\
&+\frac{(N)_{i+1/2,j+1/2}D_1[w^1]_{i+1/2,j+1/2}-(N)_{i-1/2,j+1/2}D_1[w^1]_{i-1/2,j+1/2}}{\Delta x_1}\\
&+\frac{(N)_{i+1/2,j+1/2}D_2[w^2]_{i+1/2,j+1/2}-(N)_{i-1/2,j+1/2}D_2[w^2]_{i-1/2,j+1/2}}{\Delta x_1}\\
&+\frac{(\mu)_{i,j+1}D_2[u^1]_{i,j+1}-(\mu)_{i,j}D_2[u^1]_{i,j}}{\Delta x_2}+\frac{(\mu)_{i,j+1}D_1[u^2]_{i,j+1}-(\mu)_{i,j}D_1[u^2]_{i,j}}{\Delta x_2}=0,
\end{aligned}$$

$$\begin{aligned}
&\frac{\left(K-\frac{2}{3}\mu\right)_{i+1/2,j+1/2}D_1[u^1]_{i+1/2,j+1/2}-\left(K-\frac{2}{3}\mu\right)_{i+1/2,j-1/2}D_1[u^1]_{i+1/2,j-1/2}}{\Delta x_2}\\
&+\frac{\left(K+\frac{4}{3}\mu\right)_{i+1/2,j+1/2}D_2[u^2]_{i+1/2,j+1/2}-\left(K+\frac{4}{3}\mu\right)_{i+1/2,j-1/2}D_2[u^2]_{i+1/2,j-1/2}}{\Delta x_2}\\
&+\frac{(N)_{i+1/2,j+1/2}D[w^1]_{i+1/2,j+1/2}-(N)_{i+1/2,j-1/2}D[w^1]_{i+1/2,j-1/2}}{\Delta x_2}\\
&+\frac{(N)_{i+1/2,j+1/2}D_2[w^2]_{i+1/2,j+1/2}-(N)_{i+1/2,j-1/2}D_2[w^2]_{i+1/2,j-1/2}}{\Delta x_2}\\
&+\frac{(\mu)_{i+1,j}D_2[u^1]_{i+1,j}-(\mu)_{i,j}D_2[u^1]_{i,j}}{\Delta x_1}+\frac{(\mu)_{i+1,j}D_1[u^2]_{i+1,j}-(\mu)_{i,j}D_1[u^2]_{i,j}}{\Delta x_1}=0,
\end{aligned}\tag{12}$$

$$\begin{aligned}
&\frac{(K)_{i+1/2,j+1/2}D_1[u^1]_{i+1/2,j+1/2}-(K)_{i-1/2,j+1/2}D_1[u^1]_{i-1/2,j+1/2}}{\Delta x_1}\\
&+\frac{(K)_{i+1/2,j+1/2}D_2[u^2]_{i+1/2,j+1/2}-(K)_{i-1/2,j+1/2}D_2[u^2]_{i-1/2,j+1/2}}{\Delta x_1}\\
&\frac{(N)_{i+1/2,j+1/2}D_1[w^1]_{i+1/2,j+1/2}-(N)_{i-1/2,j+1/2}D_1[w^1]_{i-1/2,j+1/2}}{\Delta x_1}\\
&\frac{(N)_{i+1/2,j+1/2}D_2[u^2]_{i+1/2,j+1/2}-(N)_{i-1/2,j+1/2}D_2[u^2]_{i-1/2,j+1/2}}{\Delta x_1}\\
&=i\omega\left(L\right)_{i,j+1/2}\left(w^1\right)_{i,j+1/2},
\end{aligned}$$

$$\begin{aligned}
&\frac{(K)_{i+1/2,j+1/2}D_1[u^1]_{i+1/2,j+1/2}-(K)_{i+1/2,j-1/2}D_1[u^1]_{i+1/2,j-1/2}}{\Delta x_2}\\
&+\frac{(K)_{i+1/2,j+1/2}D_2[u^2]_{i+1/2,j+1/2}-(K)_{i+1/2,j-1/2}D_2[u^2]_{i+1/2,j-1/2}}{\Delta x_2}\\
&\frac{(N)_{i+1/2,j+1/2}D_1[w^1]_{i+1/2,j+1/2}-(N)_{i+1/2,j-1/2}D_1[w^1]_{i+1/2,j-1/2}}{\Delta x_2}\\
&\frac{(N)_{i+1/2,j+1/2}D_2[u^2]_{i+1/2,j+1/2}-(N)_{i+1/2,j-1/2}D_2[u^2]_{i+1/2,j-1/2}}{\Delta x_2}\\
&=i\omega\left(L\right)_{i+1/2,j}\left(w^2\right)_{i+1/2,j}.
\end{aligned}$$

$$D_1[f]_{I,J}=\frac{f_{I+1/2,J}-f_{I-1/2,J}}{\Delta x_1},\quad D_2[f]_{I,J}=\frac{f_{I,J+1/2}-f_{I,J-1/2}}{\Delta x_2}\tag{13}$$

I and J in differences (13) are either integer or non-integer, and $f\in\{u^1,u^2,w^1,w^2\}$. Second derivatives are approximated by using formulae (13) twice recursively. With the definition of discrete displacement fields and finite differences described above, we approximate the first and third equations of the system (7) at nodes with indices $(i,j+1/2)$ and the second and fourth equations

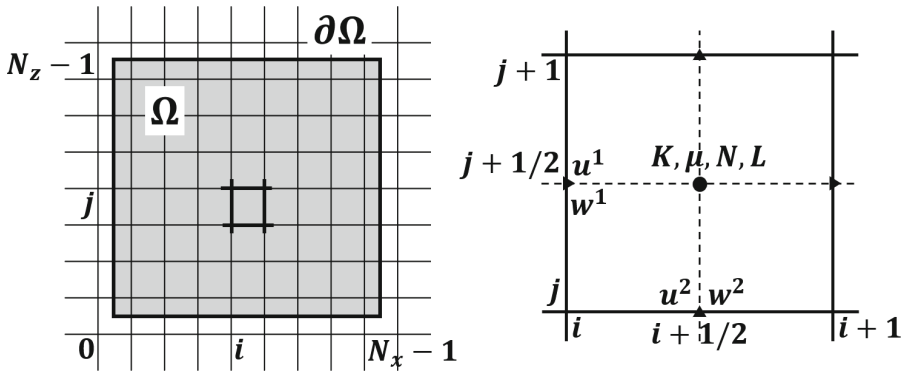


Fig. 1. Schematic images of the computational domain with grid (left) and grid cell (right).

in (7) at nodes with indices $(i+1/2, j)$. As a result, we approximate the system (7) with the following scheme:

However, not all coefficients are defined at the nodes where they appear in the scheme. In particular, in the first two equations of the system (12) shear module μ should be taken from nodes (i, j), where it is not defined explicitly, and an analogous situation happens with the coefficient L in the last pair of equations of (12). To keep the order of approximation in such cases, we apply the balance method [10] and, as a result, substitute average values using neighboring nodes of values defined as follows:

$$(\mu)_{i,j} = \frac{1}{4}\left[\frac{1}{(\mu)_{i-1/2,j-1/2}} + \frac{1}{(\mu)_{i-1/2,j+1/2}} + \frac{1}{(\mu)_{i+1/2,j-1/2}} + \frac{1}{(\mu)_{i+1/2,j+1/2}}\right]^{-1},$$
$$(L)_{i,j+1/2} = \frac{(L)_{i-1/2,j+1/2}+(L)_{i+1/2,j+1/2}}{2},$$
$$(L)_{i+1/2,j} = \frac{(L)_{i+1/2,j-1/2}+(L)_{i+1/2,j+1/2}}{2}. \tag{14}$$

As we assume the computational domain to be rectangular with the boundary going through the centers of the grid cells, in boundary nodes and near-boundary nodes, the presented Eqs. (12) make no sense because some variables appear at the nodes where they are not defined. To get rid of the undefined values and complete the resulting system in all the computational domain, we take into account boundary conditions at these nodes. In particular, we modify the Eqs. (12) using the immersed boundary technique [11] by the boundary values approximation. For example, at the left side of the boundary $\partial\Omega_L$ $(i = 1/2)$ we apply conditions (10) for the solution components and analogous grid function $(\sigma_{13})_{i,j}$ in the following way:

$$
\begin{gathered}
(\phi_{11})_{1/2,j+1/2} = (\sigma_{11})_{1/2,j+1/2} = \\
(K + \tfrac{4}{3})_{1/2,j+1/2} \frac{(u^1)_{1,j+1/2} - (u^1)_{0,j+1/2}}{\Delta x_1} + (K - \tfrac{2}{3})_{1/2,j+1/2} \frac{(u^2)_{1/2,j+1} - (u^2)_{1/2,j}}{\Delta x_2} \\
+ (N)_{1/2,j+1/2} \left(\frac{(w^1)_{1,j+1/2} - (w^1)_{1,j+1/2}}{\Delta x_1} + \frac{(w^2)_{1/2,j+1} - (w^2)_{1/2,j}}{\Delta x_2} \right), \\
(\sigma_{13})_{1,j} = \frac{(\sigma_{13})_{1/2,j} + (\sigma_{13})_{3/2,j}}{2} = \frac{(\phi_{13})_{1/2,j} + (\sigma_{13})_{3/2,j}}{2}. \\
\frac{(w^1)_{0,j+1/2} - (w^2)_{1,j+1/2}}{2} = 0,
\end{gathered}
\tag{15}
$$

The first and third equations of (15) are used to exclude $(u^1)_{0,j+1/2}$ and $(w^1)_{0,j+1/2}$ from the first and third equations of (12). The second equation of (15) according to the first equation of (5) is used to exclude $(u^1)_{0,j}$ and $(u^2)_{-1/2,j}$ from the last two terms in the second equation of (12). As a result, we obtain a closed system of linear equations to calculate displacements. Such systems can be solved by different approaches, including direct and iterative solvers. In our case, we apply Intel MKL PARDISO solver.

4 Numerical Experiment of Heterogeneous Sample Loading

To test the described algorithm, we perform numerical experiments of square sample loading in the x_1-axis direction. So we only apply non-zero normal stress σ_{11} at the boundary parts $\partial\Omega_L$ and $\partial\Omega_R$. Such numerical experiments were carried out, for example, to study wave-induced fluid flows within fractured fluid-saturated media [12–15] or estimate seismic attenuation caused by fluid flow as a part of the upscaling algorithm, where heterogeneous fluid-saturated media is approximated by an equivalent homogeneous viscoelastic media in terms of the same reaction to the same loading.

In a first test, the computational domain is presented by heterogeneous porous fluid-saturated medium (Fig. 2, left), where heterogeneities are fractures filled with more porous material, which provides more intensive fluid mobility due to the larger interfacial friction coefficient θ. The sizes of the domain in x_1 and x_2 directions are 1 m, and the single fracture is a rectangle of 0.004 m width and 0.03 m length. As can be seen in Fig. 2, single fractures form clusters going through the whole domain. The computational domain has 500 grid cells in both axes directions with a grid step of 0.002 m. Physical parameters of background and fracture-filling material models are presented in Table 1.

As we want to demonstrate the possibility of investigating wave-induced fluid flow appearing in the rock sample, we consider both low- and high-frequency cases in our experiments. We do so because fracture-to-background fluid flow usually develops intensively at relatively low frequencies, when the most intensive fracture-to-fracture fluid flow appears at relatively high ones [13,15]. To see the difference in fluid flow processes, we make two experiments of uniaxial loading at 10 Hz and 1 MHz.

The second test of sample uniaxial loading is aimed at studying the possibility of the approach to cover cases close to limit ones, where single-phase

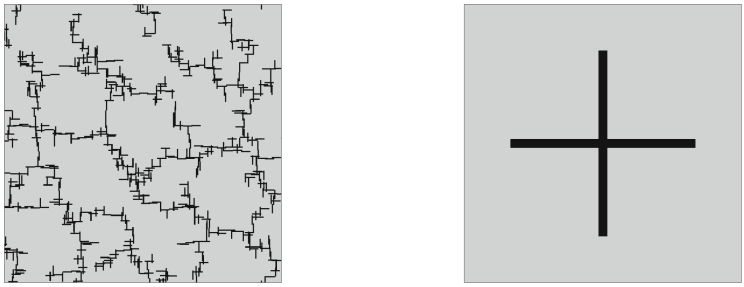


Fig. 2. Synthetic sample of fractured media (left): black color represents fractures, and gray color represents background. Model with fluid-filled cross subdomain (right): black color represents the material with porosity 0.999, gray color represents the material with porosity 0.001.

Table 1. Material properties for fractured media: background (second column) and fracture-filling material (third column); properties for media with cross: background (fourth column) and cross content (fifth column).

Parameter	Material 1	Material 2	Material 3	Material 4
Fluid density, ρ_1 $[kg/m^3]$	1040	1040	1040	1040
Solid density, ρ_2 $[kg/m^3]$	2500	2500	2500	2500
Interfacial friction coefficient, θ $[s]$	$3.36 \cdot 10^{-13}$	$3.36 \cdot 10^{-1}$	$7.8 \cdot 10^{-18}$	$4.48 \cdot 10^{-17}$
Mixture bulk modulus, K $[Pa]$	$3.94 \cdot 10^{10}$	$9.48 \cdot 10^{9}$	$3.94 \cdot 10^{10}$	$2.4 \cdot 10^{9}$
Solid shear modulus, μ $[Pa]$	$2.45 \cdot 10^{10}$	$2.45 \cdot 10^{10}$	$4.4 \cdot 10^{10}$	10^{6}
Porosity	0.05	0.2	0.001	0.999

materials (fluid, solid) are presented within the medium. Single-phase consideration is required to model fluid motion within pore space explicitly, including the pore geometry [16,17]. The problem set up is close to one in [2], where two models for fluid/solid two-phase media representation were compared. The computational domain here (Fig. 2, right) is presented by the almost purely solid background material (porosity $\alpha_1 = 0.001$), storing a cross-form subdomain containing almost only fluid (porosity $\alpha_1 = 0.999$). The square computational domain has 0.03 m sides, and the cross is formed by the intersection of two rectangular segments with a width of 0.001 m and a length of 0.02 m. Physical properties are presented in Table 1. We again apply loading along the x_1 axis, and the frequency is 1 GHz.

5 Numerical Results

In this section, we present the results of the numerical solution of Eqs. (7) using the approximation (12) for the two considered mediums (Fig. 2) described above.

In particular, we consider the corresponding part of the solution $\vec{w}$ and demonstrate its module $|\vec{w}|$ at Fig. 3 to investigate the fluid mobility within the heterogeneous media by showing the zones of intensive fluid flow and its behavior under loading at different frequencies.

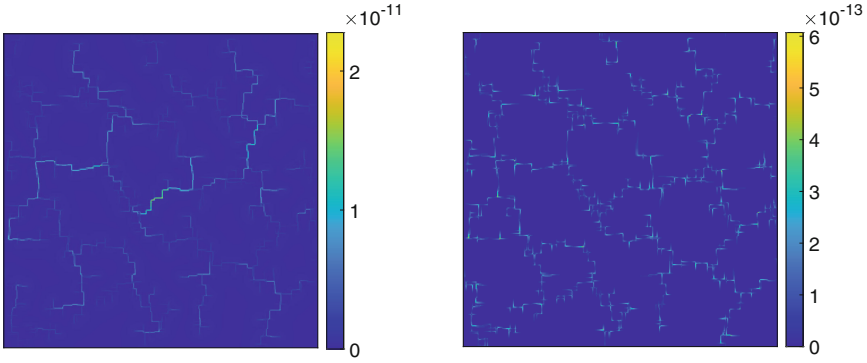


Fig. 3. Relative fluid displacement module $|\vec{w}|$ [m] within fractured media under uniaxial loading at 10 Hz (left) and 1 MHz (right).

For the first set up, fractured media in Fig. 3 we can clearly see that the most fluid motion is concentrated within the fractures, as expected, because the fluid mobility is significantly limited by the value of the interfacial friction coefficient. However, in the case of lower frequency (Fig. 3, left) we notice fluid displacement relatively small but comparable to one between the fractures. This motion represents exactly the FB-WIFF type, spreading in the fractures vicinity from the fractures. One can also observe the global nature of fluid displacement within the fracture clusters, considering it some kind of smoothed, meaning that the smallest parts of the structures (single fracture parts) are not affected by relative fluid displacement. It is caused by the characteristic length of the phenomena defined by the frequency (analogous to the wave propagation case, when the wavelength does not allow for oscillations to develop in significantly smaller structures in propagation time). Conversely, the high-frequency case results in no fluid displacement of order of one within the fractures, as demonstrated in Fig. 3. Here, we can only detect significant fluid displacement within the fractures. More specifically, this displacement consists of the smaller (in terms of the typical distance) perturbations that highlight the whole fracture system, including the smallest embranchments comparable to a single fracture size. So both frequency cases result in the observable fluid flow between the fractures (FF-WIFF), but the behavior of these flows in these two cases is obviously not the same. Note that even if we see the orders of displacement moduli in both cases, we cannot compare the intensities of fluid motion between the two cases yet, as for this the absolute (and not relative, as in the Fig. 3) values of displacements should be considered. Finally, all observed behavior is qualitatively similar to

an analogous study performed using Biot theory [13]. Unfortunately, we have no possibility to compare quantitatively results based on our mathematical model and Biot model due to the sufficiently different nature of their origins, and the same material properties for both models can result in different responses [5].

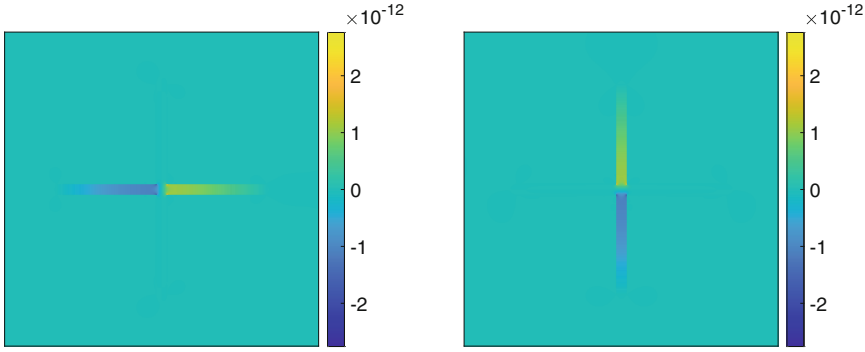


Fig. 4. Relative fluid displacement module components w_1 (left) and w_2 (right) [m]. in media with the fluid-saturated cross-form subdomain.

In the second case (media with cross-form heterogeneity), relative fluid displacement $\vec{w}$ can be interpreted as an absolute one, and the mixture displacement $\vec{u}$ should be ignored, because in the considered mathematical model (1) reducing the solid phase part in the mixture to zero (i.e. $\alpha_1 \to 1$) results in the mixture velocity losing its physical sense within the system of equations and acting independently on the described fluid model. In the assumption of holding this property also in the quasi-static approximation of the model, we consider only fluid motion in the cross subdomain. Fluid displacement component fields w_1 and w_2 are demonstrated in Fig. 4. We observe the predictable symmetric behavior of fluid motion, with its intensity increasing from the ends of the cross to its center. Outside the heterogeneity, we, as expected, see no fluid motion. As with the results for fractured media, this result qualitatively agrees with the previous studies using Biot theory [2]. However, the porosity in our case is closer to limit cases, which can be a problem for Biot equations applicability. Moreover, reliable results obtained for the considered porosity value show a future transition to a pure single-phase case possible in the study. This advantage is useful for modeling the single pore and fluid behavior within it, including so-called "squirt flow" processes within it.

6 Conclusion

In our work, we presented an approach to numerical modeling of the loading of samples of heterogeneous poroelastic fluid-saturated material based on the theory of thermodynamically compatible systems. In particular, we applied

a quasi-static approximation of the propagation equations for small-amplitude waves, excluding phase acceleration from the system. By expressing stresses in terms of displacements, we obtained a system of second-order partial differential equations for mixture displacements and relative phase displacements. Closing the system by the boundary conditions, we defined the boundary value problem of sample loading. To solve the problem numerically, a second-order finite-difference scheme on a staggered grid is applied using the averaging of material parameters at the boundaries of inhomogeneities and the immersed boundary method to approximate the boundary conditions for stresses and fluid velocity. The resulting SLAE is then solved numerically by specifying the displacement fields inside the computational domain. The presented approach was tested on the problem of uniaxial loading of a fractured sample to monitor the emerging fluid flows inside the cracks. The results show the presence of both crack-to-background and crack-to-crack fluid flow at different typical frequencies, and the demonstrated fluid displacement behavior depends on the frequency of the loading process. This behavior is qualitatively similar to the results based on the well-known Biot theory of poroelasticity. Quantitative analysis of the solution by comparing our algorithm with other two-phase media approaches will be the topic to continue our study. Note that our results were obtained under the simplified assumption of an infinite shear stress relaxation time $\tau \to \infty$, so the case of finite τ will be considered in the future. Moreover, there are computational limitations when using a direct solver, and in order to apply our approach to larger computational domains, we should explore the use of other SLAE solvers, in particular, iterative ones, to obtain the SLAE solution, which is also in our future research plans.

References

1. Rubino, J.G., Muller, T.M., Guarracino, L., Milani, M., Holliger, K.: Seismoacoustic signatures of fracture connectivity. J. Geophys. Res. Solid Earth **119**(3), 2252–2271 (2014)
2. Quintal, B., Rubino, J.G., Caspari, E., Holliger, K.: A simple hydromechanical approach for simulating squirt-type flow. Geophysics **81**(4), D335–D344 (2016)
3. Godunov, S., Romenskii, E.: Elements of Continuum Mechanics and Conservation Laws. Kluwer Academic/Plenum Publishers, New York (2003)
4. Peshkov, I., Pavelka, M., Romenski, E., Grmela, M.: Continuum mechanics and thermodynamics in the Hamilton and the Godunov-type formulations. Continuum Mech. Thermodyn. **30**, 1343–1378 (2018)
5. Romenski, E., Reshetova, G., Peshkov, I., Dumbser, M.: Modeling wavefields in saturated elastic porous media based on thermodynamically compatible system theory for two-phase solid-fluid mixtures. Comput. Fluids **206**, 104587 (2020)
6. Reshetova, G., Romenski, E.: Diffuse interface approach to modeling wavefields in a saturated porous medium. Appl. Math. Comput. **398**, 125978 (2021)
7. Romenski, E., Reshetova, G., Peshkov, I.: Computational model for compressible two-phase flow in deformed porous medium. In: Gervasi, O., et al. (eds.) ICCSA 2021. LNCS, vol. 12949, pp. 224–236. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-86653-2_16

8. Romenski, E., Reshetova, G., Peshkov, I.: Two-phase hyperbolic model for porous media saturated with a viscous fluid and its application to wavefields simulation. Appl. Math. Model. **106**, 567–600 (2022)
9. Novikov, M.A., Lisitsa, V.V., Bazaikin, Y.V.: Wave propagation in fractured-porous media with different percolation length of fracture systems. Lobachevskii J. Math. **41**(8), 1533–1544 (2020)
10. Samarskii, A.A.: The Theory of Difference Schemes, Pure and Applied Mathematics, vol. 240. CRC Press, Boca Raton (2001)
11. Mittal, R., Iaccarino, G.: Immersed boundary methods. Annu. Rev. Fluid Mech. **37**(1), 239–261 (2005)
12. Quintal, B., Steeb, H., Frehner, M., Schmalholz, S.M.: Quasi-static finite-element modeling of seismic attenuation and dispersion due to wave-induced fluid flow in poroelastic media. J. Geophys. Res. **116**, B01201 (2011)
13. Rubino, J.G., Caspari, E., Müller, T.M., Milani, M., Barbosa, N.D., Holliger, K.: Numerical upscaling in 2-D heterogeneous poroelastic rocks: anisotropic attenuation and dispersion of seismic waves. J. Geophys. Res. Solid Earth **121**(9), 6698–6721 (2016)
14. Caspari, E., et al.: Attenuation mechanisms in fractured fluid-saturated porous rocks: a numerical modelling study. Geophys. Prospect. **67**(4), 935–955 (2019)
15. Solovyev, S., Novikov, M., Lisitsa, V.: A numerical investigation of wave-induced fluid flows in anisotropic fractured porous media. Comput. Math. Appl. **140**, 78–88 (2023)
16. Lissa, S., Ruf, M., Steeb, H., Quintal, B.: Digital rock physics applied to squirt flow. Geophysics **86**(4), MR235–MR245 (2021)
17. Alkhimenkov, Y., Quintal, B.: An accurate analytical model for squirt flow in anisotropic porous rocks — Part 2: complex geometry. Geophysics **87**(6), MR291–MR302 (2022)



Construction of Relative Permeability Curves by Numerical Simulation of Two-Phase Flow in 3D CT-Models

Tatyana Khachkova[1(✉)] and Vadim Lisitsa[2]

[1] Institute of Petroleum Geology and Geophysics SB RAS, Koptug Avenue 3, Novosibirsk 630090, Russia
khachkovats@ipgg.sbras.ru

[2] Institute of Mathematics SB RAS, Koptug Avenue 2, Novosibirsk 630090, Russia
lisitsavv@ipgg.sbras.ru

Abstract. The paper describes an algorithm for constructing relative phase permeability curves based on a numerical simulation of primary drainage and subsequent water re-saturation. These processes are simulated as two-phase fluid flows in three-dimensional models generated from CT-images. We use the Navier-Stokes equations to simulate the flow and the Cahn-Hilliard equation to model phase transport. In the applied phase field method, phases are specified by a concentration function. This function is smooth so that the interphase boundary is replaced by a fairly thin layer in which the values of the concentration function continuously change. This representation makes it possible to robustly calculate surface tension forces and take into account the contact angle when using the finite difference method for numerical modeling of fluid flows and phase transport.

Keywords: Two-phase flow · Phase field method · Relative phase permeability · CT-images

1 Introduction

One of the main directions in developing digital rock physics is the simulation of fluid flows at the pore scale. It is due to high interest from industry since the estimates of rock permeability, both absolute and relative, are key parameters in hydrodynamic modeling and optimization of hydrocarbon reservoir development processes.

The simplest task is the simulation of one-phase flow to estimate absolute permeability based on solving the stationary Stokes equation in pore space [1,3]. At the same time, assessments of relative phase permeability, residual oil and water saturation, as well as the construction of relative permeability curves and capillary pressure curves, require solving a much more complex problem, namely,

This study was funded by Russian Science Foundation (grant no. 21-71-20003).

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 250–262, 2024.
https://doi.org/10.1007/978-3-031-65238-7_17

the simulation of multi-phase flows in pore space with complex topology. The main problem of such modeling is considering the moving phase boundary. There are several approaches to solving this problem, for example, direct edge tracking methods [6], level-set method [5,11], phase field method [4,9,14] and others. The first technique is difficult to carry out in the three-dimensional case, particularly in regions with complicated topology. Direct tracking of the boundary requires separate consideration of each event where a droplet separates from the general flow, division of the interface into several, and so on. The second method implicitly defines an interface as the zero level of a function that specifies a signed distance. It enables the handling of complicated geometry in the computational domain. However, the numerical error in the solution obtained by this method manifests itself in a nonphysical change in the volume of the phases, which requires further regularization [7,13]. In addition, the surface tension forces arising at the interface depend on the curvature of this interface, which requires calculating the second derivative of this surface. In the case where it is specified by the level-set method, such calculations are subject to a high level of numerical error. Moreover, approximating the contact angle condition is also difficult for this method. The phase field method uses a diffuse interface technique, in which the phase boundary is smoothed over several grid cells. As a result, the concentration function becomes sufficiently smooth to be approximated by mesh functions used in finite volume, finite difference, or finite element methods [9]. In such a mathematical model, fluid flow satisfies the Navier-Stokes equation with variable fluid density and viscosity, and phase transport (concentration function) satisfies the fourth-order Cahn-Hilliard equation with nonlinear terms. Undoubtedly, such an equation goes beyond the classical theory of equations of mathematical physics, but it can be solved quite effectively using the finite difference method. Moreover, this approach is applicable for calculating flows in domains with complex topology, i.e., in the pore space of rocks.

Section 2 presents a system of Navier-Stokes-Cahn-Hilliard equations for describing two-phase fluid flows in domains with complex geometry. For this system, an explicit finite-difference approximation is given (Sect. 3), which makes it possible to calculate the solution using modern computing systems. After that, we present the algorithm for constructing the relative permeability curves. We numerically simulate the primary drainage (Sect. 4.1) with the subsequent waterflooding (Sect. 4.2). The results of numerical experiments are provided for the sandstone sample from the Bentheimer outcrop.

2 Statement of the Problem

In this study, we build a model using segmented microtomographic images of rock [2]. In such a model, a value of one corresponds to the pore space, and zero corresponds to the rock matrix. It is assumed that the rock is monomineral, which implies a constant contact angle, but the approach can be easily generalized to the case of polymineral rock. Formally, we can consider the domain (sample) $\Omega = [0; L_1] \times [0, L_2] \times [0, L_3]$, where L_j is the length of the sample in

the direction x_j, $j = 1, 2, 3$. Two non-overlapping subregions are distinguished in this domain: the impermeable rock matrix Ω_s and the pore space Ω_p. Next, it is necessary to introduce the boundaries of the computational domain, making it possible to specify their boundary conditions. Firstly, Γ denotes the interface between the pore space and the rock matrix. Secondly, Γ_b are the sides of the sample: $x_2 = 0$, $x_2 = L_2$, $x_3 = 0$, $x_3 = L_3$. These boundaries can be permeable or completely impenetrable, depending on the formulation of the problem. For this work, they are assumed to be impenetrable to correspond to laboratory experiments measuring permeability. It is also assumed that the contact angles at the boundaries Γ and Γ_b coincides. Thirdly, the next boundaries are introduced: Γ_{in} for an inlet, corresponding to $x_1 = 0$, and Γ_{out} for an outlet, $x_1 = L_1$, through which the fluid flow is maintained.

Fluid flow in the pore space is described by the Stokes equation, in which the nonlinear term is neglected due to the low flow velocity:

$$\begin{aligned} &\frac{\partial \rho(\psi)\vec{u}}{\partial t} = -\nabla p + 2\nabla \cdot (\nu \epsilon(\vec{u})) + \vec{G}(\psi), \\ &\nabla \cdot (\vec{u}) = 0. \end{aligned} \tag{1}$$

In these equations, $\rho(\psi)$ is the density of the fluid, which depends on a specific phase, $\vec{u}$ is the velocity vector, p is the pressure, $\nu(\psi)$ is the viscosity of the fluid, which also depends on the phase, $2\epsilon(u) = \nabla\vec{u} + \nabla\vec{u}^T$ is doubled strain tensor, and $\vec{G}(\psi)$ are external forces. Here, it is assumed that gravitational forces can be neglected so that external forces are due only to interfacial surface tension.

Phase transport satisfies the Cahn-Hilliard equation [9]:

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

Here, $\psi \in [0, 1]$ is the order parameter that defines a specific phase, μ is the chemical potential (auxiliary variable), M is the mobility, which is usually chosen as a constant, ε is the auxiliary parameter that determines the width of the diffuse interfacial boundary. This parameter must be proportional to the square of the grid step. The potential $F(\psi)$ is determined as

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

Several models can represent external forces caused by interfacial surface tension, but within the context of this work, the following relationship is considered:

$$\vec{G}(\psi) = -\frac{6\sqrt{2}}{\varepsilon}\psi \nabla \mu. \tag{3}$$

It is also necessary to introduce the boundary conditions:

$$\begin{aligned} &\vec{u} = 0, \quad \nabla\mu \cdot \vec{n} = 0, \nabla\psi \cdot \vec{n} = -\frac{\sqrt{2}}{\varepsilon}(\psi^2 - \psi)\cos(\theta), && \vec{x} \in \Gamma_b \cup \Gamma, \\ &p = p_{out}, \nabla\mu \cdot \vec{n} = 0, \nabla\psi \cdot \vec{n} = 0, && \vec{x} \in \Gamma_{out}, \\ &q = q_{in}, \quad \nabla\mu \cdot \vec{n} = 0, \psi = \Psi_{in}, && \vec{x} \in \Gamma_{in}. \end{aligned} \tag{4}$$

The first line of conditions is established at impermeable boundaries, ensuring fluid adhesion (velocity equal to zero) and a contact angle equal to θ for the first

phase ($\psi = 1$). The second line of condition, at the outlet, allows the phase to flow freely out and fixes the pressure on the right side of the sample. The third line determines the fluid flow rate on the left side of the sample and sets the phase distribution at the inlet. The initial conditions are assumed to be given; the distribution $\psi(0, \vec{x})$ is given.

3 Finite Difference Approximation

To describe the approximation for the system of Eqs. (1), (2), first, it is convenient to consider a semi-discrete formulation, in which discretization is carried out only in time. In this case, an explicit finite-difference scheme of the first order of approximation in time is used, and the solution to the Navier-Stokes equation is calculated using the projection method. Then, the finite-difference scheme has the form:

$$\begin{aligned}
&\rho(\psi^n)\tfrac{\vec{u}^{n+1/2}-\vec{u}^n}{\tau} = 2\nabla\cdot(\nu(\psi^n)\epsilon(\vec{u}^n)) + \vec{G}(\psi^n),\\
&\nabla\cdot\left(\tfrac{1}{\rho(\psi^n)}\nabla p^{n+1}\right) = \tfrac{1}{\tau}\nabla\cdot\vec{u}^{n+1/2},\\
&\rho(\psi^n)\tfrac{\vec{u}^{n+1}-\vec{u}^{n+1/2}}{\tau} = \nabla p^{n+1},\\
&\tfrac{\psi^{n+1}-\psi^n}{\tau} + \vec{u}^{n+1}\cdot\nabla\psi^n = M\Delta\mu^n,\\
&\mu^n = F'(\psi^n) - \varepsilon^2\Delta\psi^n,
\end{aligned} \tag{5}$$

where τ is the time step of the scheme. It is clear from this representation that all variables except pressure are calculated explicitly, and it is necessary to solve the Poisson equation to determine the pressure on a new layer. To solve it, we use the method of biconjugate gradients with a pseudo-spectral preconditioner, presented in work [8].

Constructing an approximation in space requires introducing staggered grids such that the pressure and order parameter are defined in nodes with integer indices $p_{ijk} = p((x_1)_i, (x_2)_j, (x_3)_k)$ and $\psi_{ijk} = \psi((x_1)_i, (x_2)_j, (x_3)_k)$, and the velocity components are defined in nodes with one half-integer index, i.e., $(u_1)_{i+1/2jk} = u_1((x_1)_{i+1/2}, (x_2)_j, (x_3)_k)$, $(u_2)_{ij+1/2k} = u_2((x_1)_i, (x_2)_{j+1/2}, (x_3)_k)$, $(u_3)_{ijk+1/2} = u_3((x_1)_i, (x_2)_j, (x_3)_{k+1/2})$. Then, the finite-difference scheme will look like this:

$$\begin{aligned}
&\rho\left(\hat{\psi}^n_{i+1/2jk}\right)\tfrac{(u_1)^{n+1/2}_{i+1/2jk}-(u_1)^n_{i+1/2jk}}{\tau} = 2\sum_{m=1}^{3} D_m[\nu(\hat{\psi})\epsilon_{1m}]^n_{i+1/2jk} + G_1(\hat{\psi}^n_{i+1/2jk}),\\
&\rho\left(\hat{\psi}^n_{ij+1/2k}\right)\tfrac{(u_2)^{n+1/2}_{ij+1/2k}-(u_2)^n_{ij+1/2k}}{\tau} = 2\sum_{m=1}^{3} D_m[\nu(\hat{\psi})\epsilon_{2m}]^n_{ij+1/2k} + G_2(\hat{\psi}^n_{ij+1/2k}),\\
&\rho\left(\hat{\psi}^n_{ijk+1/2}\right)\tfrac{(u_3)^{n+1/2}_{ijk+1/2}-(u_3)^n_{ijk+1/2}}{\tau} = 2\sum_{m=1}^{3} D_m[\nu(\hat{\psi})\epsilon_{3m}]^n_{ijk+1/2} + G_3(\hat{\psi}^n_{ijk+1/2}),
\end{aligned} \tag{6}$$

$$
\begin{aligned}
&(\nu(\hat{\psi})\epsilon_{11})^n_{ijk} = \nu(\hat{\psi}^n_{ijk}) D_1[u_1]^n_{ijk},\\
&(\nu(\hat{\psi})\epsilon_{22})^n_{ijk} = \nu(\hat{\psi}^n_{ijk}) D_2[u_2]^n_{ijk},\\
&(\nu(\hat{\psi})\epsilon_{33})^n_{ijk} = \nu(\hat{\psi}^n_{ijk}) D_3[u_3]^n_{ijk},\\
&(\nu(\hat{\psi})\epsilon_{23})^n_{ij+1/2k+1/2} = \tfrac{1}{2}\nu(\hat{\psi}^n_{ij+1/2k+1/2}) \left(D_3[u_2]^n_{ij+1/2k+1/2} + D_2[u_3]^n_{ij+1/2k+1/2}\right),\\
&(\nu(\hat{\psi})\epsilon_{13})^n_{i+1/2jk+1/2} = \tfrac{1}{2}\nu(\hat{\psi}^n_{i+1/2jk+1/2}) \left(D_3[u_1]^n_{i+1/2jk+1/2} + D_1[u_3]^n_{i+1/2jk+1/2}\right),\\
&(\nu(\hat{\psi})\epsilon_{12})^n_{i+1/2j+1/2k} = \tfrac{1}{2}\nu(\hat{\psi}^n_{i+1/2j+1/2k}) \left(D_1[u_2]^n_{i+1/2j+1/2k} + D_2[u_1]^n_{i+1/2j+1/2k}\right),\\
&\sum_{m=1}^{3} Q_m[p,\rho(\psi)]^{n+1}_{ijk} = \tfrac{1}{\tau}\sum_{m=1}^{3} D_m[u_m]^{n+1/2}_{ijk},\\
&\rho\left(\hat{\psi}^n_{i+1/2jk}\right)\tfrac{(u_1)^{n+1}_{i+1/2jk} - (u_1)^{n+1/2}_{i+1/2jk}}{\tau} = D_1[p]^{n+1}_{i+1/2jk},\\
&\rho\left(\hat{\psi}^n_{ij+1/2k}\right)\tfrac{(u_2)^{n+1}_{ij+1/2k} - (u_2)^{n+1/2}_{ij+1/2k}}{\tau} = D_2[p]^{n+1}_{ij+1/2k},\\
&\rho\left(\hat{\psi}^n_{ijk+1/2}\right)\tfrac{(u_3)^{n+1}_{ijk+1/2} - (u_3)^{n+1/2}_{ijk+1/2}}{\tau} = D_3[p]^{n+1}_{ijk+1/2},\\
&\mu^n_{ijk} = 2\psi^n_{ijk}(\psi^n_{ijk}-1)(2\psi^n_{ijk}-1) - \varepsilon^2\sum_{m=1}^{3} D^2_m[\psi]^n_{ijk},\\
&\tfrac{\psi^{n+1}_{ijk} - \psi^n_{ijk}}{\tau} + \sum_{m=1}^{3} D^F_m[u^{n+1}_m \psi^n]_{ijk} = M\sum_{m=1}^{3} D^2_m[\mu]^n_{ijk}.
\end{aligned}
\tag{7}
$$

In this notation, finite-difference operators have the following form:

$$
\begin{aligned}
&D^2_1[q]^n_{IJK} = \tfrac{q^n_{I+1JK} - 2q^n_{IJK} + q^n_{I-1JK}}{h_1^2},\\
&Q_1[p,\rho(\psi)]^{n+1}_{ijk} = \tfrac{1}{h_1}\left(\tfrac{1}{\hat{\rho}(\psi^n_{i+1/2jk})}\tfrac{p^{n+1}_{i+1jk} - p^{n+1}_{ijk}}{h_1} - \tfrac{1}{\hat{\rho}(\psi^n_{i-1/2jk})}\tfrac{p^{n+1}_{ijk} - p^{n+1}_{i-1jk}}{h_1}\right),\\
&D_1[q]^N_{IJK} = \tfrac{q^N_{I+1/2JK} - q^N_{I-1/2JK}}{h_1},\\
&D^F_1[u^{n+1}_1\psi^n]_{ijk} = \tfrac{F^1_{i+1/2jk} - F^1_{i-1/2jk}}{h_1},\\
&F^1_{i+1/2jk} = \begin{cases} (u_1)^{n+1}_{i+1/2jk}\psi^n_{i+1jk}, & (u_1)^{n+1}_{i+1/2jk} < 0,\\ (u_1)^{n+1}_{i+1/2jk}\psi^n_{ijk}, & (u_1)^{n+1}_{i+1/2jk} > 0. \end{cases}
\end{aligned}
\tag{8}
$$

Here h_1 is the grid step in the direction x_1. Indices written in lowercase letters can only take integer values, while capital letters imply that they can be either whole or half-integer values. Operators that approximate derivatives with respect to two other spatial coordinates can be obtained by appropriate substitution of indices. It should be noted that the resulting difference scheme provides first-order approximation in time and space. In this case, the order of approximation in space can be increased using more accurate schemes for approximating phase transport. Currently, the simplest upwind scheme is used for this purpose, but it can be replaced by a third-order WENO scheme [10,12]. Note, that components of the strain tensor (7) are not computed or stored explicitly in real simulations, but they are substituted to the Eqs. (6). However, for the sake of simplicity we provide the Eqs. (6) and (7) separately.

The described algorithm's implementation is focused on using graphic co-processors. Explicit schemes are used at all stages except for solving the Poisson equation. They are easily implemented on CUDA. The algorithm presented in [8] is used to solve the Poisson equation.

4 Numerical Experiments

In our numerical experiments we use the CT-scans of a sandstone sample from the Bentheimer outcrop with the size of 200^3 voxels and the resolution of 1.72 μm per voxel. In our work [3], we investigated the influence of the scale of a digital image of a rock, that is, its size and resolution, on the assessment of various parameters, particularly transport parameters. We followed the definition of statistically representative volume, or SREV, presented in [15]: a volume is statistically representative if the variance of the property being valued does not exceed a certain level (say, 10%) of its average value for all statistically equivalent measurements. Based on this definition, the representative size for transport parameters was shown to be larger than what we had available. However, the calculated estimates were quite close to the values obtained in the laboratory. In this work, we used a digital sample, which is also not representative (according to the specified criterion) for assessing transport parameters. However, the absolute permeability calculated using the above approach is also close to the laboratory one. Therefore, this sample is used to represent the algorithm for constructing relative permeability curves.

We numerically simulate a steady-state laboratory method for measuring relative permeability to construct such curves. The first step of this method is to saturate the rock sample with 100% water and measure the absolute permeability. In the second step, only oil is injected into the sample until a steady-state regime is achieved, after which the irreducible water saturation and the maximum oil relative permeability are measured. This process is called primary drainage. Next, both fluids are injected in different ratios, with the amount of water being minimal at first. For each subsequent experiment, the proportion of water gradually increases until 100% water is reached. For each experiment and subsequent measurements, it is necessary to establish a steady-state mode. The described process is called waterflooding (or water re-saturation, inhibition). Let us describe in detail the numerical modeling of these processes.

4.1 Numerical Simulation of Primary Drainage

Under natural conditions, a reservoir, initially completely saturated with water, is gradually filled with oil, which migrates from the source rock. Numerical simulation of drainage, in which the wetting phase (water in case of water-wet system) decreases, repeats this process, i.e., oil is injected into a rock sample completely filled with water. It is done until the oil displaces all possible water so that irreducible water saturation is reached. It is the moment when a reservoir is discovered in nature, and at this time, the oil's relative permeability is the maximum. In contrast, the water's relative permeability becomes equal to zero. These are the endpoints of the drainage relative permeability curves and the starting points of the waterflooding relative permeability curves. The second set of curves is significant for the petroleum industry; we will describe their construction in the following subsections.

When simulating drainage, we use the following parameters: sample size is 200^3 voxels, porosity is $\phi = 21.2\%$, mesh spacing is $1.75 * 10^{-6}$ m, water and oil density are $\rho = [1000; 880]$ kg/m^3, fluids viscosity $\nu = [3.8 * 10^{-4}; 4.027 * 10^{-3}]$ Pa $\cdot$ s, interfacial tension $\sigma = 2.571 * 10^{-2}$ N/m, contact angle for the first fluid (water) $\theta = 38.7°$. We specify the flow velocity at the inlet $v = 1 * 10^{-1}$ m/s and the time required to reach steady-state $T = 3.7 * 10^{-3}$ s. During this time, five volumes of pore space will pass through the sample. The calculated time step is approximately $\tau = 1.00385 * 10^{-8}$ s. In addition, we define the water/oil ratio for the injected mixture as the ratio of the water volume to the total volume. In the case of drainage, this ratio is equal to 0 since only oil is injected.

We perform three numerical experiments simulating flow in three spatial directions. During the experiments, we record the distribution of the phase field, pressure, and velocity at each point of the digital sample for certain points in time. From the data obtained, we can calculate the resulting water saturation, as well as the effective and relative permeabilities. The last parameters are determined from the following relations:

$$k_w = \frac{q_w \nu_w L}{A \Delta P_w}, \; k_o = \frac{q_o \nu_o L}{A \Delta P_o}, \; k_{rw} = \frac{k_w}{k}, \; k_{ro} = \frac{k_o}{k}, \tag{9}$$

where k_w, k_o are the effective water and oil permeabilities, q_w, q_o are water and oil flow rates, ν_w, ν_o are fluid viscosities, L is the sample length, A is cross-sectional area, $\Delta P_w, \Delta P_o$ are the pressure drops, k_{rw}, k_{ro} are the relative water and oil permeabilities and k is the absolute permeability.

Figure 1 illustrates the described simulation of the drainage process for a sandstone sample from the Bentheimer outcrop.

4.2 Numerical Simulation of Water Re-saturation

At a certain stage of oil field development, the need arises for forced injection of water into the reservoir. It is done in order to displace oil from it. At this stage, it is necessary to have waterflooding relative permeability curves to predict fluid behavior and provide the most efficient hydrocarbon production.

In the steady-state laboratory method for measuring relative permeability, the water re-saturation is the third step, following the drainage. Here, both fluids are simultaneously injected into the sample in a certain ratio; then, the experimenter waits for the steady-state regime to be established, after which the parameters are measured, and the next points on the relative permeability curves are calculated. Each laboratory experiment can take several hours to several days depending on the absolute permeability, i.e., this method is very time-consuming. However, it is considered more accurate than the displacement method, in which only water is pumped, and which requires analytical interpretation of the results.

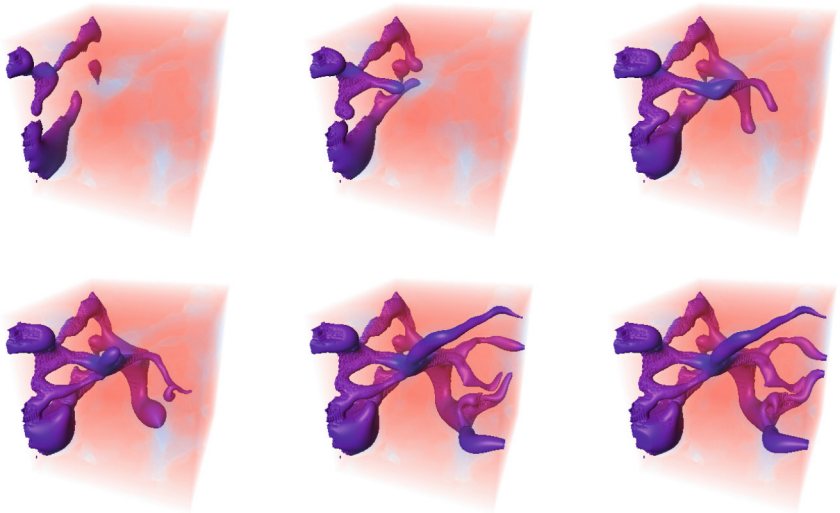


Fig. 1. The relative arrangement of phases (water has a blue translucent color, oil has a lilac color) in the pore space when water is displaced by oil at different points in time. (Color figure online)

To numerically simulate the waterflooding process we, just like in the laboratory, perform a series of experiments. In the first numerical experiment, the proportion of water in the injected fluid mixture is minimal, for example, 0.1, 0.05, or 0.025; in each subsequent experiment, this proportion increases. It continues until only water is injected, i.e. its ratio to the total volume will reach 1. As at the drainage simulation, the phase field, pressure, and velocity distribution are recorded during experiments, from which the water saturation, effective, and relative permeabilities are then calculated using formulas (9). The results obtained are added to the curves. The smaller the step in the water fraction, the more accurate the curves should be. Additionally, we perform this numerical simulation in two different ways. In the first, we simultaneously generate models for all experiments of the first series, starting with the model of the drainage stage, changing only the proportion of water in the mixture, and calculating the results of all experiments in this series in parallel. In the second way, we perform all experiments sequentially, i.e., the model obtained in the previous step is used for the next calculation, in which the proportion of injected water is also increased. The second approach requires more time and effort, so testing whether it gives more accurate results than the first is necessary.

Figures 2, 3 illustrate the described simulation of the water re-saturation process for the sandstone sample. Figure 2 shows that with a water fraction in the mixture of 0.1, 0.3, and 0.6, the oil remains in the system, but different parts of it are replaced by the water.

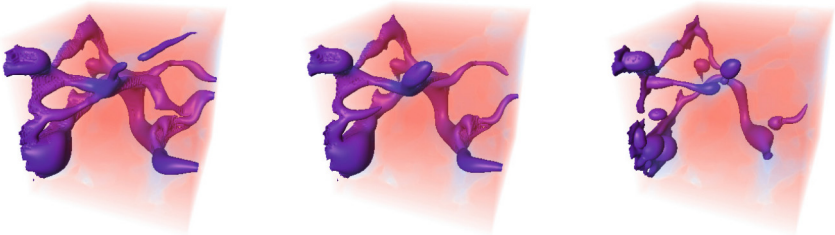


Fig. 2. The relative arrangement of phases (water has a blue translucent color, oil has a lilac color) in the pore space after the waterflooding, the proportions of injected water in the mixture are 0.1, 0.3, 0.6 for images from left to right. (Color figure online)

Figure 3 shows how, with a water fraction of 1, i.e., when only water is injected into the sample, the oil is almost completely replaced by water during the waterflooding process. It is the last experiment in each series, and as a result, the oil's relative permeability becomes zero, and the residual oil saturation is determined from the corresponding calculated water saturation value.

As in laboratory steady-state experiments, to determine the relative permeabilities, it is necessary to wait until a steady-state regime is established; also, in numerical experiments, we wait until the calculated values (the water saturation and the phase permeabilities) are established. Figures 4, 5 show how the process of establishing these values occurs. Figure 4 shows how water saturation gradually increases when injecting a mixture with a water ratio of 0.8. At approximately the 30th snap out of 100, the value reaches a plateau, and starting from the 50th snap, it practically does not deviate from the average value calculated for the snaps 50–100. The values of effective permeabilities for water and oil behave similarly. Figure 5 shows that the values approach the average (calculated for the last 50 steps) approximately at the 20th snap. After the 50th snap, they practically do not differ from this average.

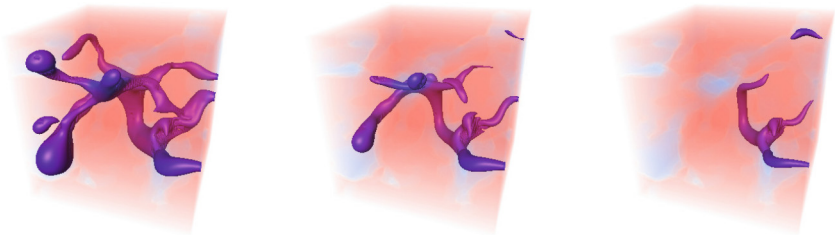


Fig. 3. The relative arrangement of phases (water has a blue translucent color, oil has a lilac color) in the pore space during the last waterflooding experiment, when only the water is injected into the system, at different times. (Color figure online)

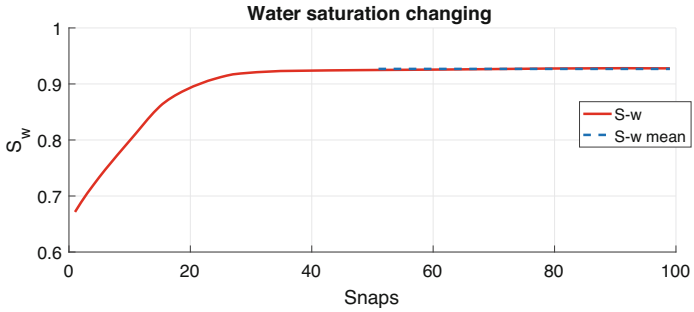


Fig. 4. Water saturation depending on the time of the experiment; a mixture with a water ratio of 0.8 is injected into the sample. The mean value calculated for the snaps 50–100 is shown with a dashed blue line. (Color figure online)

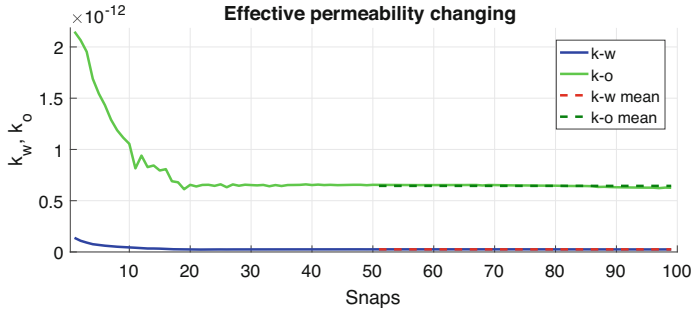


Fig. 5. Water and oil effective permeabilities depending on the time of the experiment. The mean values calculated for the snaps 50–100 are shown with dashed red and dark green lines. (Color figure online)

4.3 Effective and Relative Permeabilities Curves

To construct the effective and relative permeability curves, we first numerically simulate the drainage, resulting in the first points of each graph; after that, we simulate the waterflooding and calculate the next 10 points corresponding to water-to-total mixture ratios from 0.1 to 1.

We perform numerical experiments in three different spatial directions: x, y, and z. As already mentioned, two series for the waterflooding are performed for all directions: parallel calculations and sequential ones. Thus, we obtain four effective and relative permeability curves for each direction (two for water and two for oil). In Figs. 6, 7, dashed lines with the triangle points indicate curves obtained by a fast parallel method (first series), and solid lines with the star points indicate curves obtained by a sequential method (second series) when the model from the previous experiment is used for the subsequent one. The legend shows the correspondence of the graphs to the directions.

Figures 6, 7 show that the results of the two series are very close to each other, but the graphs for the second series are slightly smoother. Thus, if we

need to perform calculations quickly, we can use the first method, i.e., perform all calculations simultaneously. If we want to get more accurate results, it is better to perform all experiments sequentially, one after another.

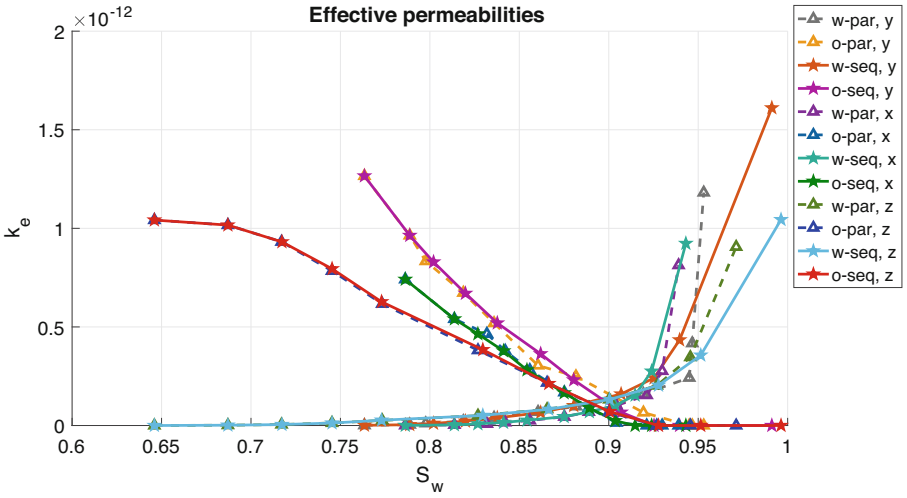


Fig. 6. Effective permeabilities curves for the Bentheimer sandstone sample for various spacial directions. The results of the first experiment series are shown by the dashed lines, and the solid lines show the results of the second series.

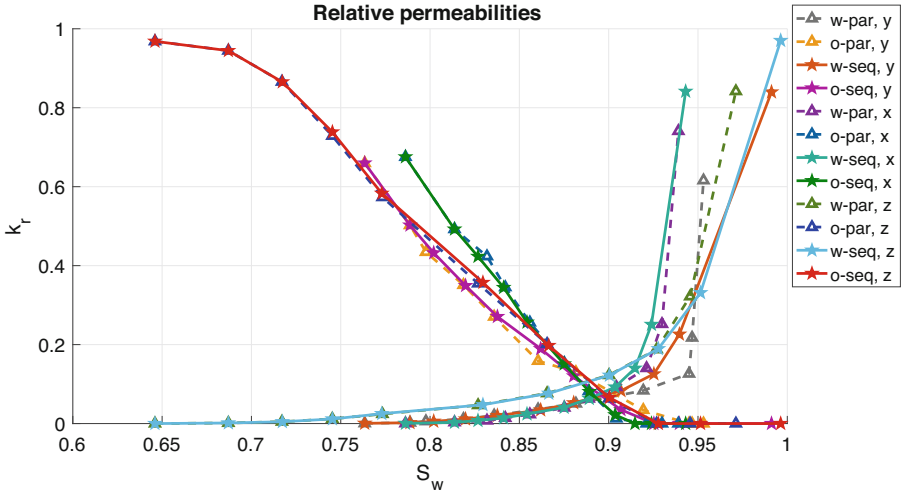


Fig. 7. Relative permeabilities curves for the Bentheimer sandstone sample for different spacial directions. The results of the first experiment series are shown by the dashed lines, and the solid lines show the results of the second series.

5 Conclusion

In this paper, we describe the numerical algorithm for constructing the relative phase permeability curves in a non-destructive way using the CT-images of rock samples. In our case, the rock is mono-mineral, but the approach can be easily generalized to the case of a poly-mineral rock. In the algorithm presented, we numerically simulate a steady-state laboratory method for measuring relative permeability. This laboratory method is very time-consuming but produces accurate results. Following this method, we numerically simulate the primary drainage and subsequent water re-saturation as two-phase fluid flows in three-dimensional models. We use the Navier-Stokes equations to simulate the flow and the Cahn-Hilliard equation to model phase transport. In the applied phase field method, phases are specified by a concentration function. This function is smooth so that the interphase boundary is replaced by a fairly thin layer in which the values of the concentration function continuously change. This representation makes it possible to robustly calculate surface tension forces and take into account the contact angle when using the finite difference method for numerical modeling of fluid flows and phase transport. Moreover, this approach is applicable for calculating flows in domains with complex topology, i.e., in the pore space of rocks.

All numerical experiments were performed on a sandstone sample from the Bentheimer outcrop. When simulating waterflooding, we conducted two series of experiments. All experiments were calculated in parallel in the first fast series, with the same model (obtained after drainage) but with different water ratios in the injected mixture. The experiments of the second series were carried out sequentially, one after another. The model from the previous experiment was used for the next one, and the water ratios were also changed. A comparison of the results of the two series showed that the obtained relative permeability curves are very close to each other, but the curves constructed during the second series are slightly smoother.

Thus, if we need to perform calculations quickly and for a larger number of points, it is better to use the first method, i.e. perform all calculations simultaneously. If we want to get more accurate results, it is better to carry out all experiments sequentially, one after another. However, this will require significantly more time and effort. Despite this, the numerical method is still less time-consuming than the laboratory one.

References

1. Andra, H., et al.: Digital rock physics benchmarks - Part I: imaging and segmentation. Comput. Geosci. **50**, 25–32 (2013)
2. Andra, H., et al.: Digital rock physics benchmarks - Part II: computing effective properties. Comput. Geosci. **50**, 33–43 (2013)
3. Bazaikin, Y., et al.: Effect of CT image size and resolution on the accuracy of rock property estimates. J. Geophys. Res. Solid Earth **122**(5), 3635–3647 (2017)

4. Boyer, F., Lapuerta, C., Minjeaud, S., Piar, B., Quintard, M.: Cahn-Hilliard/Navier-stokes model for the simulation of three-phase flows. Transp. Porous Media **82**(3), 463–483 (2010)
5. Gibou, F., Fedkiw, R., Osher, S.: A review of level-set methods and some recent applications. J. Comput. Phys. **353**, 82–109 (2018)
6. Groot, R.D.: Second order front tracking algorithm for Stefan problem on a regular grid. J. Comput. Phys. **372**, 956–971 (2018). https://doi.org/10.1016/j.jcp.2018.04.051
7. Jettestuen, E., Friis, H.A., Helland, J.O.: A locally conservative multiphase level set method for capillary-controlled displacements in porous media. J. Comput. Phys. **428**, 109965 (2021). https://doi.org/10.1016/j.jcp.2020.109965
8. Khachkova, T., Lisitsa, V., Reshetova, G., Tcheverda, V.: GPU-based algorithm for evaluating the electrical resistivity of digital rocks. Comput. Math. Appl. **82**, 200–211 (2021)
9. Kim, J.: Phase-field models for multi-component fluid flows. Commun. Comput. Phys. **12**(3), 613–661 (2012)
10. Luo, K., Zhuang, Z., Fan, J., Haugen, N.E.L.: A ghost-cell immersed boundary method for simulations of heat transfer in compressible flows under different boundary conditions. Int. J. Heat Mass Transf. **92**, 708–717 (2016)
11. Osher, S., Fedkiw, R.P.: Level set methods: an overview and some recent results. J. Comput. Phys. **169**(2), 463–502 (2001)
12. Prokhorov, D., Lisitsa, V., Khachkova, T., Bazaikin, Y., Yang, Y.: Topology-based characterization of chemically-induced pore space changes using reduction of 3d digital images. J. Comput. Sci. **58**, 101550 (2022)
13. Sussman, M., Fatemi, E.: An efficient, interface-preserving level set redistancing algorithm and its application to interfacial incompressible fluid flow. SIAM J. Sci. Comput. **20**(4), 1165–1191 (1999)
14. Yang, J., Kim, J.: A novel Cahn-Hilliard-Navier-stokes model with a nonstandard variable mobility for two-phase incompressible fluid flow. Comput. Fluids **213**, 104755 (2020). https://doi.org/10.1016/j.compfluid.2020.104755
15. Zhang, D., Zhang, R., Chen, S., Soll, W.E.: Pore scale study of flow in porous media: scale dependency, rev, and statistical rev. Geophys. Res. Lett. **27**(8), 1195–1198 (2000)

NDM-Net and Model Changes

Elena Gondyul(✉), Kirill Gadylshin, Vadim Lisitsa, and Dmitry Vishnevsky

Institute of Petroleum Geology and Geophysics SB RAS,
Koptug Avenue 3, Novosibirsk, Russia 630090
gondyulea@ipgg.sbras.ru

Abstract. The paper discusses the problem of suppressing the numerical error, which together represents the numerical dispersion and the error of the roughened velocity model. Such a numerical error is suppressed by using a NDM-net (Numerical Dispersion Mitigation neural network), which was originally proposed to map seismograms with numerical dispersion to accurate solutions calculated on a fine grid. This approach makes it possible to accelerate the seismic modeling by 6 times without significant changes in quality. Also, the paper discusses two-stage training of NDM-net, in which the numerical dispersion is first suppressed, and then the interface error.

Keywords: Seismic modelling · Deep learning · Numerical Dispersion

1 Introduction

Seismic modeling has an important role in elucidating the laws of seismic wave propagation and response mechanisms in complex media. A widely used method for modeling wave fields is the finite difference method [11,16,23,26] due to its simple implementation and the use of a small amount of memory. However, when using coarse grids to reduce computational costs, numerical dispersion occurs. Along with other classical grid methods, such as finite elements [32], spectral elements [25,33], discontinuous Galerkin [3,13,20] pseudo-spectral methods [4, 19] and others, moreover, require sufficiently large computational costs to obtain solutions without numerical errors. Thus, if the grid step has been halved, the number of grid points increases in 16 times.

One way to reduce the numerical error is to use an increased approximation order (the formal order of the basis function) [9,12,18]. However, this approach reduces the Courant number, which makes the stability condition more stringent. Also, the length of the stencil (for finite differences) or the size of the local mass and stiffness matrices for the discontinuous Galerkin method also increases, requiring more floating-point operations per grid node.

G. Gondyul performed numerical simulations on NDM-net application, V. Lisitsa suggested the approach to data suppression via FFT, K. Gadylshin developed the algorithm to apply the U-net to dispersion suppression and D.Vishnevsky performed seismic modelling under the support of Russian Science Foundation grant no. 22-11-00004.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 263–275, 2024.
https://doi.org/10.1007/978-3-031-65238-7_18

Another approach is to use numerical dispersion suppression schemes [2,6,14] in the finite difference method. However, this approach also has a large number of flops per grid node and a strict stability condition.

The presented methods are complemented by procedures prior to modeling wave fields. An alternative method is to use deep learning methods that are applied to seismic fields calculated on a coarse grid. Thus, we can reduce computational costs and get enough high-quality data, since neural networks are good approximators of the transition operator by extracting high-level features from the data.

Deep learning has become an integral part of seismic processing nowadays. Methods such as Neural Networks are used to interpolate missed traces [17,31], suppress white and ground noise [24,30], detect first arrival picking [22,29] and so on. The Numerical Dispersion Mitigation neural network (NDM-net) [5] has been proposed to suppress numerical dispersion in seismic fields. Such a network has performed well in suppressing the numerical dispersion associated with temporal and spatial coordinates.

In this paper, we explore the possibilities of NDM-net, particularly, whether it is possible to use NDM-net when changing not only the computational grid but also changing the sampling rate of the velocity model. Such a study will allow us to expand the functionality of the NDM-net.

2 Statement of the Problem

2.1 Seismic Modelling

Consider the elastic wave equation written in the Cartesian coordinates in terms of velocity and stress tensor components:

$$\begin{aligned}
\rho\frac{\partial u_x}{\partial t} &= \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xz}}{\partial z},\\
\rho\frac{\partial u_z}{\partial t} &= \frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{zz}}{\partial z},\\
\frac{\partial \sigma_{xx}}{\partial t} &= (\lambda+2\mu)\frac{\partial u_x}{\partial x} + \lambda\frac{\partial u_z}{\partial z} + \hat{f}_{xx},\\
\frac{\partial \sigma_{zz}}{\partial t} &= \lambda\frac{\partial u_x}{\partial x} + (\lambda+2\mu)\frac{\partial u_z}{\partial z} + \hat{f}_{zz},\\
\frac{\partial \sigma_{xz}}{\partial t} &= \mu\frac{\partial u_x}{\partial z} + \mu\frac{\partial u_z}{\partial x} + \hat{f}_{xz},
\end{aligned} \tag{1}$$

where $\vec{u} = (u_x, u_z)^T$ is the particle velocity vector, σ_{xx}, σ_{zz}, σ_{xz} are the stress tensor components, $\rho = \rho(x,z)$ is the mass density, $\lambda = \lambda(x,z)$ and $\mu = \mu(x,z)$ are the Lame's parameters, and $\hat{f}_{xx} = f_{xx}(t)\delta(x-x_s)\delta(z-z_s)$, $\hat{f}_{zz} = f_{zz}(t)\delta(x-x_s)\delta(z-z_s)$, $\hat{f}_{xz} = f_{xz}(t)\delta(x-x_s)\delta(z-z_s)$ are the seismic moments tensor. Typically, the point sources are considered, thus $\delta(x-x_s)$ is the Kronecker's delta function, where (x_s, z_s) is the source location coordinates. The time wavelets $f_{xx}(t)$, $f_{zz}(t)$, $f_{xz}(t)$ are defined by a band-limited impulse.

System of Eq. (1) is solved in a limited area $D = [x_s - L_x, x_s + L_x] \times [0, Z]$, which is determined for each source x_s with maximal offset L_x and depth of the model Z.

The classical 2D acquisition system is considered. The system consists of N_s sources located on a surface with coordinates $(x_s, 0)$, and N_r receivers for each source with coordinates $(x_r^j(x_s), 0)$.

For convenience, we introduce the offset coordinates $x_o^j = x_r^j - x_s$, where $x_o \in [L_o, L_o]$ changes with fixed interval for each source positions with maximal offset $L_o \leq L_x$. We consider seismograms, denoted as $\vec{u}^{x_s}(t, x_o)$, as a solution to system (1).

2.2 Finite-Difference Scheme

The Lame coefficients are used as parameters for the system (1), which are obtained from knowledge about the velocity of seismic waves in elastic media. For each source, a velocity model is considered in a limited volume $M(x, z, x_s^j) \subset M(x, z)$, where $M(x, z)$ is the entire model. The model itself can be refined or not refined, depending on the discretization step of the model h_x^M, h_y^M, and is interpolated for further numerical modeling using the finite difference method.

We used staggered-grid finite differences [8,9,26,27] to solve system (1), which is described in detail in [5]. We will denote $\vec{u_h}(t, x_0, x_s^k)$ as a numerical solution of system (1) using a grid step $h = h_x = h_z$.

Second-order in time and fourth-order accurate in space scheme defined on spaced grids are used:

$$\begin{aligned}
&\rho D_t[u_x]^{n+1/2}_{i+1/2,j} = D_x[\sigma_{xx}]^{n+1/2}_{i+1/2,j} + D_z[\sigma_{xz}]^{n+1/2}_{i+1/2,j},\\
&\rho D_t[u_z]^{n+1/2}_{i+1/2,j} = D_x[\sigma_{xz}]^{n+1/2}_{i+1/2,j} + D_z[\sigma_{zz}]^{n+1/2}_{i+1/2,j},\\
&D_t[\sigma_{xx}]^{n}_{i,j} = (\lambda + 2\mu) D_x[u_x]^{n}_{i,j} + \lambda D_z[u_z]^{n}_{i,j} + (\hat{f}_{xx})^{n}_{i,j},\\
&D_t[\sigma_{zz}]^{n}_{i,j} = \lambda D_x[u_x]^{n}_{i,j} + (\lambda + 2\mu) D_z[u_z]^{n}_{i,j} + (\hat{f}_{zz})^{n}_{i,j},\\
&D_t[\sigma_{xz}]^{n}_{i+1/2,j+1/2} = \mu D_x[u_z]^{n}_{i+1/2,j+1/2} + \mu D[u_x]^{n}_{i+1/2,j+1/2} + (\hat{f}_{xz})^{n}_{i+1/2,j+1/2},
\end{aligned} \tag{2}$$

where finite-difference operators is defined as:

$$D_t[f]^N_{I,J} = \frac{f^{N+1/2}_{I,J} - f^{N-1/2}_{I,J}}{\tau} \approx \frac{\partial f}{\partial t}, \tag{3}$$

$$\begin{aligned}
D_x[f]^N_{I,J} &= \tfrac{9}{8} \tfrac{f^N_{I+1/2,J} - f^N_{I-1/2,J}}{h_x} - \tfrac{1}{24} \tfrac{f^N_{I+3/2,J} - f^N_{I-3/2,J}}{h_x} \approx \tfrac{\partial f}{\partial x},\\
D_z[f]^N_{I,J} &= \tfrac{9}{8} \tfrac{f^N_{I,J+1/2} - f^N_{I,J-1/2}}{h_z} - \tfrac{1}{24} \tfrac{f^N_{I,J+3/2} - f^N_{I,J-3/2}}{h_z} \approx \tfrac{\partial f}{\partial z},
\end{aligned} \tag{4}$$

where $f(t, x, z)$ is a smooth enough function.

Here, we do not specify the way to treat the coefficients of the Eq. $\lambda(x, z)$, $\mu(x, z)$, and $\rho_{x,z}$ it is discussed in [10,15,16,28].

2.3 NDM-Net

Here, we will briefly describe the Numerical Dispersion Mitigation neural network (NDM-net), which was suggested in [5]. To begin with, we need to calculate seismograms $\vec{u_{h_2}}(t, x_0, x_s^k)$ for all source positions x_s^k using a coarse grid with

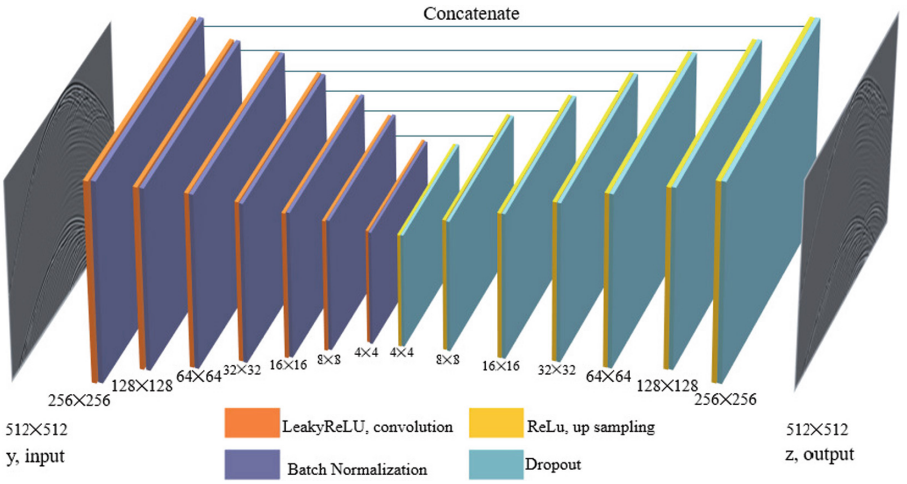


Fig. 1. NDM-net architecture

characteristic grid step h_2. This allows to obtain an inaccurate solution with less computational costs. At the same time, it is possible to compute a small number of seismograms $\vec{u_{h_1}}(t, x_o, x_s^l)$, where $l \in S_t \subset \{1, ..., N_s\}$ is the index of source included in the training sample, using a fine enough mesh with characteristic grid step $h_1 < h_2$ to obtain an accurate solution. After that neural network is trained by optimizing the loss function:

$$L(\Theta) = \mathbf{E}_{l \in S_t} \left[\left\| \vec{u}_{h_1}(t, x_o, x_s^l) - F\left[\vec{u}_{h_2}(t, x_o, x_s^l), \Theta\right] \right\|_1 \right],$$

where $F : \vec{u}_{h_2} \rightarrow \vec{u}_{h_1}$ is the operator represented by a multilayer perceptron, $\Theta = \{\mathbf{W}, \mathbf{b}\}$ is the network parameters, which includes the weight matrix $\mathbf{W}$ and bias $\mathbf{b}$, $\mathbf{E}_{l \in S_t}$ is a mean over the training dataset.

We used U-shaped network based on U-net architecture [21] as shown in Fig. 1. And includes 8 downsampling layers with convolution operations, activation function $ReLU(\cdot) = \max(0, \cdot)$ and 8 upsampling layers with deconvolution operations and $LeakyReLU(\cdot) = \max(1, \cdot) + c\min(1, \cdot)$ as an activation function with slope factor $c = 0.2$. The training parameters are given in Table 1. They were selected in the course of numerous experiments during the study.

It is obvious that a different network architecture can be promising in seismic data processing. For example, [7] suggests using a cascade of dense U-net for denoising images, [30] uses a deep convolutional neural network for denoising and ground-roll attenuation of seismic data, and [17] uses cGan for interpolation of seismic data. However, our task requires fairly fast learning and good generalizability, which is provided by U-net.

We used two NVIDIA GeForce RTX 3090 cards with 8 GB of memory and Intel Core CPU with 256 GB RAM to train NDM-net. Calculations were performed using the Pytorch framework.

Table 1. Hyperparameters and training parameters

Parameter	Value
Learning rate	from 0.0002 to 0.0001 during epoch
Momentum parameters	$\beta_1 = 0.5, \beta_2 = 0.999$
Batch size	1
The number of epochs	750
Optimization algorithm	Adaptive Momentum
Optimality criterion	Mean Absolute Error

3 Numerical Experiments

In this section, we provide the analysis of numerical experiments with regularly located sources as training samples for a neural network. Firstly, we show the input data that is used for training and testing the NDM-net. Secondly, we train the NDM-net on this data, and then we calculate the initial error and the error between the generated and correct data on the test dataset (previously unseen by the NDM-net).

3.1 Input Data

In this section, we describe Marmousi model and acquisition systems that is used for subsequent experiments.

Initially, the Marmousi model was created based on a profile passing through the North Quenguela and included 160 layers [1]. The size of the model is 3501.25 m $\times$ 17001.25 m in vertical and horizontal directions, respectively. The P-wave velocity varies greatly from 1500 m/s to 4500 m/s and is shown in Fig. 2.

The acquisition system consists of 171 sources with a distance of 100 m between each other and receivers that are located at a distance of 25 m from each other. For each source position, the wave field is recorded by 513 receivers with an offset of about 6.5 km. The source is a Ricker wavelet with a central frequency of 30 Hz.

We simulated 6 sets of seismograms that differ from each other in the sampling steps in elastic medium models h^M and the sampling steps of the computational grid h. Let the seismogram be denoted as d^{M_*,S_*}, where M_* and S_* denote the model discretization and computational grid respectively. The description of the calculated grids for each type of seismogram is given in Table 2. The sampling rate was 1 ms, and the recording length was 5 s.

The Fast Fourier Transform (FFT) is used to compress seismograms and translate them into the frequency domain. Such a procedure allows us to reduce the data dimension from 512×5000 to 512^2 by taking only the positive part of the spectrum and throwing out high-frequency information, which contains mainly noise. The non-trivial part of the FFT of the one seismogram is shown

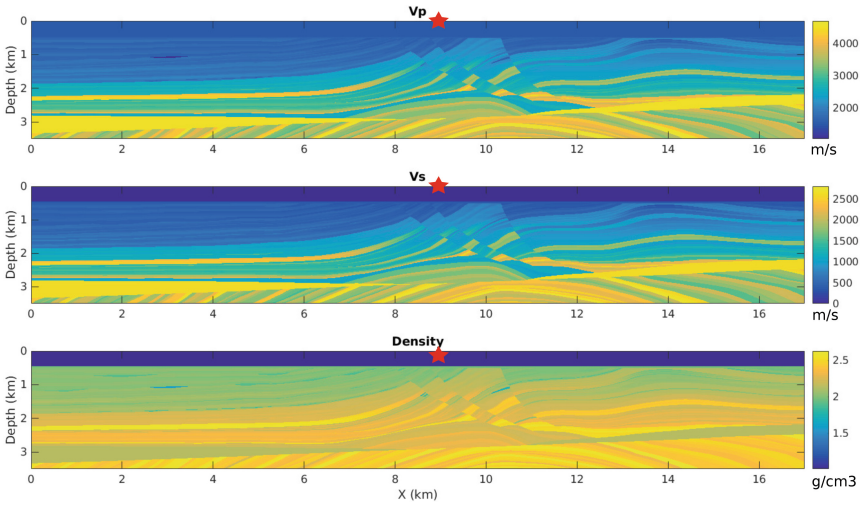


Fig. 2. Marmousi velocity model

Table 2. Sampling steps in an elastic medium model and a computational grid for calculating datasets

Data	$h_x^M = h_z^M$, m	$h_x = h_z$, m
d^{M_1,S_1}	1.25	1.25
d^{M_2,S_1}	2.5	1.25
d^{M_2,S_2}	2.5	2.5
d^{M_5,S_1}	5	1.25
d^{M_5,S_2}	5	2.5
d^{M_5,S_5}	5	5

in Fig. 3. It is limited by the frequency interval $[0, 102.4]$ Hz with the frequency resolution of $1/5$ Hz.

Thus, we have formed datasets to investigate the effect of errors in models on the results of using a NDM-net.

4 Training Results

We trained a total of 12 NDM-net on different training datasets with a size of 60% of the total number of seismograms N_s. Consider d as the seismogram with numerical dispersion as the target data and d' as the labeled data (clear seismogram) and d_{gen} as the generated by NDM-net seismogram. A training dataset is a pair consisting of $\{d, d'\}_{i=1}^{N}$, where N is the size of the dataset.

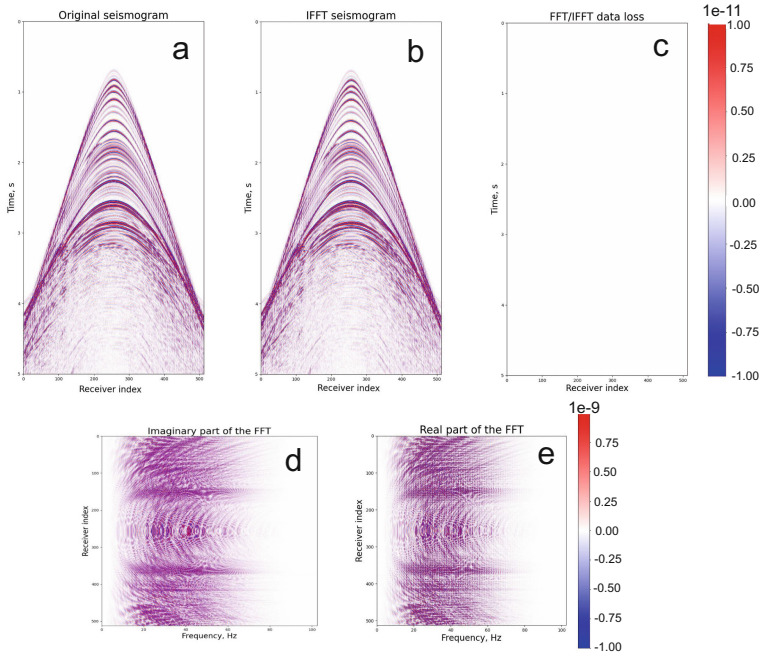


Fig. 3. Transfer of seismic data to the frequency domain and back to the time domain: a) the original seismogram; b) the inverse Fourier transform; c) the absolute difference between the original and inverse Fourier transform; d), e) the Fourier transform (real and imaginary part).

The relative L_2 norm to estimate the error between the data and verify the performance of the NDM-net is used:

$$L_2^{rel}(d', d_{gen}) = \frac{||d' - d_{gen}||_2}{||d'||_2} \times 100\%.$$

All types of training samples, as well as the average of relative error, are shown in Table 3.

The error is reduced by the largest number of times, in the case when the initial error is large ($d^{M_5,S_5} \rightarrow d^{M_5,S_2}$, $d^{M_5,S_5} \rightarrow d^{M_5,S_1}$, $d^{M_5,S_5} \rightarrow d^{M_2,S_2}$, $d^{M_5,S_5} \rightarrow d^{M_1,S_1}$). Herewith, it is well suppressed both in the case of a fixed discretization of the model and a variation in the step of the computational grid and when both discretizations are changed. In the case when initial error is small, the best options are those in which the discretization by the model h^M is fixed and the step of the calculation grid h varies ($d^{M_2,S_1} \rightarrow d^{M_1,S_1}$), as well as with a fixed h and the changes of the h^M ($d^{M_2,S_2} \rightarrow d^{M_2,S_1}$).

A possible explanation for this is the introduction of unnecessary noise when approximating the transition operator by NDM-net $G : d \rightarrow d'$. Then, in the case of a large initial error, processes suppressing numerical dispersion prevail,

and in the case when the initial error is small, the artifacts introduced by the neural network begin to dominate.

The worst result (a ratio of about one) was obtained when transition from seismograms calculated with relatively coarse sampling of the model and a fine computational grid to more accurate one ($d^{M_5 S_1} \rightarrow d^{M_2,S_1}$, $d^{M_5,S_1} \rightarrow D^{M_1,S_1}$).

Table 3. Training results on different type of the training dataset with size of 60% of the total sources number

d	d'	$L_2^{rel}(d,d')$ (Init)	$L_2^{rel}(d_{gen},d')$	$\frac{L_2^{rel}(d,d')}{L_2^{rel}(d_{gen},d')}$
d^{M_5,S_5}	d^{M_5,S_2}	65.83	27.42	**2.4**
	d^{M_5,S_1}	60.31	25.5	**2.36**
	d^{M_2,S_2}	51.58	28.33	1.82
	d^{M_1,S_1}	55.32	30.96	1.78
d^{M_5,S_2}	d^{M_5,S_1}	21.18	17.14	1.24
	d^{M_2,S_2}	33.76	19.18	1.76
	d^{M_2,S_1}	26.06	23.04	1.13
d^{M_5,S_1}	d^{M_2,S_1}	19.58	18.46	1.06
	d^{M_1,S_1}	25.26	20.18	1.25
d^{M_2,S_2}	d^{M_2,S_1}	27.49	17.19	1.59
	d^{M_1,S_1}	20.62	17.72	1.16
d^{M_2,S_1}	d^{M_1,S_1}	18.54	11.01	1.68

4.1 Two Stage of Training NDM-Net

In order to reduce the calculation time of seismograms, we implemented two stages of neural network training. The procedure was as follows: first, the NDM-net is trained to translate the most rough data d to more accurate d', and then using the generated data d_{gen}, we formed the new training dataset. Next, the NDM-net is trained for transition the generated data d^{gen} to the data that is the most free from numerical dispersion available d''.

For example, the performance of trained NDM-net corresponding to transition $d^{M_5,S_5} \rightarrow d^{M_5,S_1} \rightarrow d^{M_1,S_1}$ was $< \frac{L_2^{rel}(d^{M_5,S_5},d^{M_1,S_1})}{L_2^{rel}(d_{gen}^{M_1,S_1},d^{M_1,S_1})} >= 1.97$. This indicator showed that a single-stage transition provides lower performance than a two-stage one (Fig. 4).

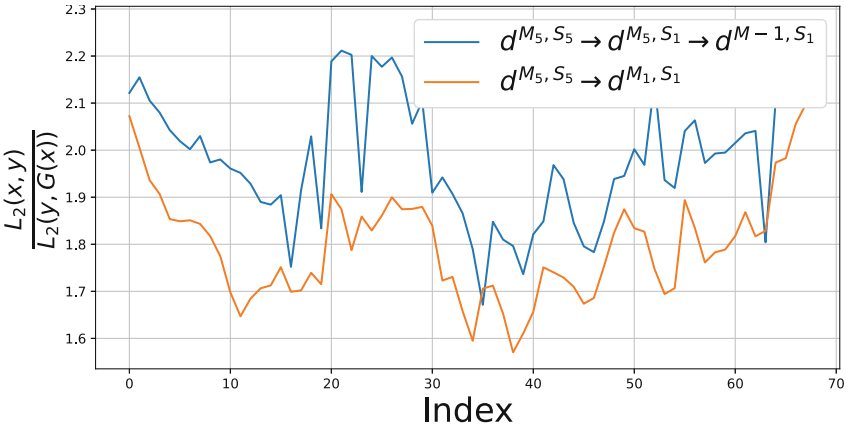


Fig. 4. Perfomance of Two-Stage NDM-net and Onet-stage NDM-net

4.2 Zero Offset

It is also important to build a zero-offset to verify our algorithm and visualize the profit of the NDM-net. Consider the transitions $d^{M_5,S_5} \rightarrow d^{M_1,S_1}$, $d^{M_5,S_5} \rightarrow d^{M_5,S_1}$ and $d^{M_5,S_1} \rightarrow d^{M_1,S_1}$ and illustrate in Fig. 5(a,b,c) the Initial Zero-Offset I^{M_5,S_5}, Zero Offset with coarse sampling of the model and a fine computational grid I^{M_5,S_1} and the accurate Zero Offset I^{M_1,S_1}. We also provided Zero Offsets in Fig. 5(d,e,f) obtained by applying a corresponding NDM-net to

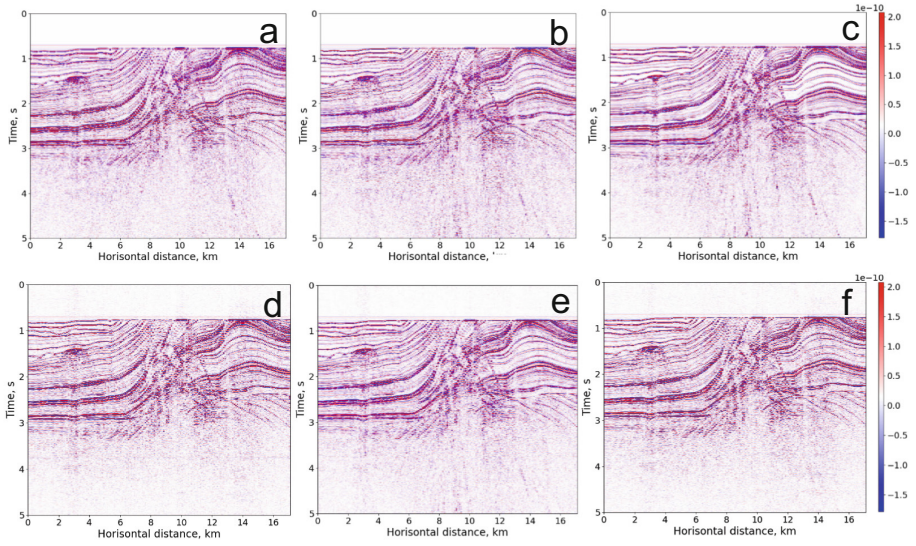


Fig. 5. Zero-Offset corresponding to seismograms modelled using a different discretizations (top row): a) I^{M_5,S_5}; b) I^{M_5,S_1}; c) I^{M_5,S_1} and the NDM-net prediction (bottom row): d) $I_{gen}^{M_5,S_5 \rightarrow M_1,S_1}$; e) $I_{gen}^{M_5,S_1 \rightarrow M_1,S_1}$; f) $I_{gen}^{M_5,S_5 \rightarrow M_5,S_1}$

translate from the roughest to the accurate seismograms $I_{gen}^{M_5,S_5 \to M_1,S_1}$, from seismograms devoid of numerical dispersion, but not the interface error, to the accurate seismograms $I_{gen}^{M_5,S_1 \to M_1,S_1}$ and from the roughest to seismograms without numerical dispersion, but with an interface error $I_{gen}^{M_5,S_5 \to M_5,S_1}$. The Fig. 6

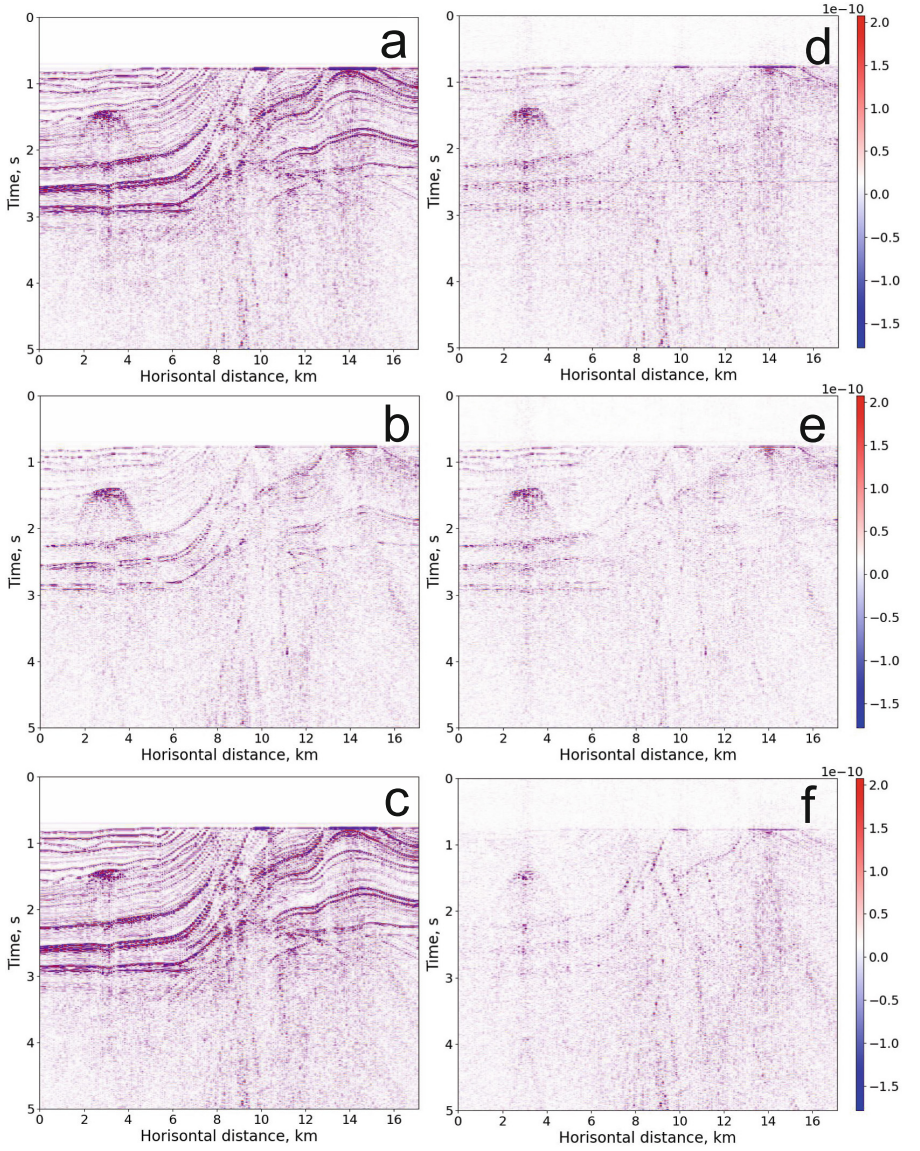


Fig. 6. Absolute error in the Zero-Offset corresponding to seismograms modelled using a different discretizations (left): a) $|I^{M_5,S_5} - I^{M_1,S_1}|$; b) $|I^{M_5,S_1} -^{M_1,S_1}|$; c) $|I^{M_5,S_5} - I^{M_5,S_1}|$ and the difference between the fine-grid data and NDM-net prediction (right): d) $|I_{gen}^{M_5,S_5 \to M_1,S_1} - I^{M-1,S_1}|$; e) $|I_{gen}^{M_5,S_1 \to M_1,S_1} - I^{M_1,S_1}|$; f) $|I_{gen}^{M_5,S_5 \to M_5,S_1} - I^{M_5,S_1}|$

also shows the absolute initial difference and the difference between the predicted data and fine-grid data.

The initial difference $L_2^{rel}(I^{M_5,S_5}, I^{M_1,S_1})$ is 79.7%, while the error between Zero-Offset obtained from generated seismograms by NDM-net $L_2^{rel}(I^{M_1,S_1}, I_{gen}^{M_1,S_1}) = 37.7\%$. In the case where only the error associated with the coarse sampling of the velocity model is suppressed, the final error was $L_2^{rel}(I^{M_5,S_1}, I_{gen}^{M_1,S_1}) = 28.9\%$, while the initial error was $L_2^{rel}(I^{M_5,S_1}, I^{M_1,S_1}) = 36.7\%$. When only the numerical dispersion is suppressed, the initial error was $L_2^{rel}(I^{M_5,S_5}, I^{M_5,S_1}) = 87.4\%$, while the error between the Zero Offset, which is obtained from predicted seismograms, and fine-grid seismograms was $L_2^{rel}(I^{M_5,S_5}, I_{gen}^{M_5,S_1}) = 31.9\%$.

This only confirms the conclusion that the NDM-net is more willing to suppress an error that has a large value, that is, a numerical dispersion. However, even with the largest variation in the model grids and computational grids, it is possible to mitigate the numerical dispersion by a factor of 2 for such a representation.

5 Conclusion

The NDM-net is presented, which was initially implemented to suppress numerical dispersion in seismic waves associated with a change in the computational grid. The paper expands the functionality of the NDM-net in case the grid according to the velocity model has also been changed. Thus, we have two types of numerical errors: numerical dispersion and interface error. It is shown that NDM-net effectively reduces both errors. However, the NDM-net suppresses the error well only if it is large enough (most often with a difference in the computational grids). Nevertheless, the results indicate the applicability of the network in the case of a coarsening of the model interface.

References

1. Brougois, A., Bourget, M., Lailly, P., Poulet, M., Ricarte, P., Versteeg, R.: Marmousi, model and data (05 1990). https://doi.org/10.3997/2214-4609.201411190
2. Chen, J.B.: A 27-point scheme for a 3D frequency-domain scalar wave equation based on an average-derivative method. Geophys. Prospect. **62**(2), 258–277 (2014)
3. Dumbser, M., Kaser, M.: An arbitrary high-order discontinuous galerkin method for elastic waves on unstructured meshes - ii. the three-dimensional isotropic case. Geophys. J. Int. **167**(1), 319–336 (2006). https://doi.org/10.1111/j.1365-246X.2006.03120.x
4. Fornberg, B.: The pseudospectral method: accurate representation of interfaces in elastic wave calculations. Geophysics **53**(5), 625–637 (1988)
5. Gadylshin, K., Vishnevsky, D., Gadylshina, K., Lisitsa, V.: Numerical dispersion mitigation neural network for seismic modeling. Geophysics **87**(3), T237–T249 (2022)
6. He, Z., Zhang, J., Yao, Z.: Determining the optimal coefficients of the explicit finite-difference scheme using the remez exchange algorithm. Geophysics **84**(3), S137–S147 (2019). https://doi.org/10.1190/geo2018-0446.1

7. Jia, F., Wong, W.H., Zeng, T.: Ddunet: dense dense u-net with applications in image denoising. IEEE/CVF International Conference on Computer Vision Workshops (ICCVW), pp. 354–364 (2021)
8. Kostin, V., Lisitsa, V., Reshetova, G., Tcheverda, V.: Local time-space mesh refinement for simulation of elastic wave propagation in multi-scale media. J. Comput. Phys. **281**, 669–689 (2015)
9. Levander, A.: Fourth-order finite-difference p-s. Geophysics **53**, 1425–1436 (11 1988). https://doi.org/10.1190/1.1442422
10. Lisitsa, V., Podgornova, O., Tcheverda, V.: On the interface error analysis for finite difference wave simulation. Comput. Geosci. **14**(4), 769–778 (2010)
11. Lisitsa, V., Vishnevskiy, D.: Lebedev scheme for the numerical simulation of wave propagation in 3D anisotropic elasticity. Geophys. Prospect. **58**(4), 619–635 (2010). https://doi.org/10.1111/j.1365-2478.2009.00862.x
12. Lisitsa, V.: Dispersion analysis of discontinuous Galerkin method on triangular mesh for elastic wave equation. Appl. Math. Modell. **40**, 5077–5095 (2016). https://doi.org/10.1016/j.apm.2015.12.039
13. Lisitsa, V., Tcheverda, V., Botter, C.: Combination of the discontinuous Galerkin method with finite differences for simulation of seismic wave propagation. J. Comput. Phys. **311**, 142–157 (2016)
14. Liu, Y., Sen, M.K.: Acoustic VTI modeling with a time-space domain dispersion-relation-based finite-difference scheme. Geophysics **75**(3), A11–A17 (2010)
15. Moczo, P., Kristek, J., Vavrycuk, V., Archuleta, R.J., Halada, L.: 3D heterogeneous staggered-grid finite-difference modeling of seismic motion with volume harmonic and arithmetic averagigng of elastic moduli and densities. Bull. Seismol. Soc. Am. **92**(8), 3042–3066 (2002)
16. Moczo, P., Kristek, J., Galis, M.: The finite-difference modelling of earthquake motion: Waves and Ruptures. Cambridge University Press (2014)
17. Oliveira, D., Ferreira, R., Silva, R., Brazil, E.V.: Interpolating seismic data with conditional generative adversarial networks. IEEE Geosci. Remote Sens. Lett. **15**(12), 1952–1956 (2018)
18. O'Reilly, O., Lundquist, T., Dunham, E.M., Nordstrom, J.: Energy stable and high-order-accurate finite difference methods on staggered grids. J. Comput. Phys. **346**, 572–589 (2017). https://doi.org/10.1016/j.jcp.2017.06.030
19. Pleshkevich, A., Vishnevskiy, D., Lisitsa, V.: Sixth-order accurate pseudo-spectral method for solving one-way wave equation. Appl. Math. Comput. **359**, 34–51 (2019)
20. Puente, J., Kaser, M., Dumbser, M., Igel, H.: An arbitrary high-order discontinuous Galerkin method for elastic waves on unstructured meshes iv. anisotropy. Geophys. J. Int. **169**(3), 1210–1228 (2007). https://doi.org/10.1111/j.1365-246X.2007.03381.x
21. Ronneberger, O., Fischer, P., Brox, T.: U-Net: convolutional networks for biomedical image segmentation. In: Navab, N., Hornegger, J., Wells, W.M., Frangi, A.F. (eds.) Medical Image Computing and Computer-Assisted Intervention – MICCAI 2015: 18th International Conference, Munich, Germany, October 5-9, 2015, Proceedings, Part III, pp. 234–241. Springer International Publishing, Cham (2015). https://doi.org/10.1007/978-3-319-24574-4_28
22. Saad, O.M., Chen, Y.: Capsphase: capsule neural network for seismic phase classification and picking. IEEE Trans. Geosci. Remote Sens. **60**, 1–11 (2022)
23. Saenger, E.H., Gold, N., Shapiro, S.A.: Modeling the propagation of the elastic waves using a modified finite-difference grid. Wave Motion **31**, 77–92 (2000)

24. Sang, Y., Peng, Y., Lu, M., Li., L.: Seisdenet: an intelligent seismic data denoising network for the internet of things. J. Cloud Comp. **12**, 34 (2023)
25. Tromp, J., Komatitsch, D., Liu, Q.: Spectral-element and adjoint methods in seismology. Commun. Comput. Phys. **3**(1), 1–32 (2008)
26. Virieux, J.: P-SV wave propagation in heterogeneous media: velocity-stress finite-difference method. Geophysics **51**(4), 889–901 (1986)
27. Virieux, J., Calandra, H., Plessix, R.E.: A review of the spectral, pseudo-spectral, finite-difference and finite-element modelling techniques for geophysical imaging. Geophys. Prospect. **59**(5), 794–813 (2011). https://doi.org/10.1111/j.1365-2478.2011.00967.x
28. Vishnevsky, D., Lisitsa, V., Tcheverda, V., Reshetova, G.: Numerical study of the interface errors of finite-difference simulations of seismic waves. Geophysics **79**(4), T219–T232 (2014)
29. Wamriew, D., Pevzner, R., Maltsev, E., Pissarenko, D.: Deep neural networks for detection and location of microseismic events and velocity model inversion from microseismic data acquired by distributed acoustic sensing array. Sensors **21** (2021)
30. Yu, S., Ma, J., Wang, W.: Deep learning for denoising. Geophysics **84**, 1–107 (2019)
31. Yu, S., Ma, J., Zhang, X., Sacchi, M.D.: Interpolation and denoising of high-dimensional seismic data by learning a tight frame. Geophysics **80**, V119–V132 (2015)
32. Zhang, J., Verschuur, D.J.: Elastic wave propagation in heterogeneous anisotropic media using the lumped finite-element method. Geophysics **67**(2), 625–638 (2002)
33. Zhang, Y., Fisser, J., Gerritsma, M.: A hybrid mimetic spectral element method for three-dimensional linear elasticity problems. J. Comput. Phys. **433**, 110179 (2021). https://doi.org/10.1016/j.jcp.2021.110179



Effective Numerical Dispersion Suppression in 3D Seismic Modeling

Kirill Gadylshin, Vadim Lisitsa(✉), Kseniia Gadylshina, and Dmitry Vishnevsky

Institute of Petroleum Geology and Geophysics SB RAS, Koptug Avenue 3, Novosibirsk 630090, Russia
lisitsavv@ipgg.sbras.ru

Abstract. The paper presents a novel method for 3D seismic modeling, combining classical grid-based methods such as finite difference methods with deep learning techniques to reduce numerical dispersion in the synthetic seismograms modeled on a coarse grid. The approach consists of three main steps. First, the inaccurate solution corresponding to the entire set of sources is computed on a coarse enough grid. Second, an accurate but computationally demanding fine-grid solution is simulated for a small number of sources to get a training dataset. Third, the neural network is trained to map coarse-grid solution to the fine-grid solution and then applied to the entire dataset. Through empirical investigation on a complex 3D SEG/EAGE Overthrust velocity model, the study highlights the significant reduction in computation time up to a factor of 15 for realistic 3D velocity models. This innovative approach offers promising advancements in seismic data processing and modeling.

Keywords: seismic modeling · 3D residual U-net · deep learning · numerical dispersion

1 Introduction

Modeling the synthetic seismograms for a single seismic source demands considerable computational resources, particularly in traditional numerical methods [13]. However, seismic acquisition systems commonly involve multiple seismic sources, exacerbating computational costs. One approach to mitigate this challenge involves reducing the problem's dimensionality, which is achieved by reducing degrees of freedom or grid nodes. Increasing the spatial grid step represents one such strategy. However, this tactic introduces numerical errors, notably numerical dispersion, when employing even-order approximations [1,9].

The advent of deep learning has brought about a seismic processing revolution, facilitating automated and more precise interpretation of seismic data

The Research Was Supported by the Russian Science Foundation Grant No. 22-11-00004.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 276–289, 2024.
https://doi.org/10.1007/978-3-031-65238-7_19

[16]. Being complex and multidimensional, seismic data often exceeds traditional processing techniques' capacity to detect subtle features and patterns. Deep learning algorithms, by contrast, possess the ability to learn from extensive sets of labeled data and discern patterns within seismic data that may challenge human interpretation [7]. This advancement holds promise for improving seismic imaging, refining reservoir characterization, and enabling more accurate predictions of subsurface properties. Moreover, deep learning presents opportunities for reducing processing time and costs, thereby enhancing the efficiency and cost-effectiveness of seismic exploration. Applying machine learning techniques for post-processing seismic data has demonstrated considerable potential, as evidenced by prior research [8,11]. [6] propose an NDM-net artificial neural network that effectively suppresses numerical dispersion in pre-calculated wave fields recorded at the free surface.

Frequency-domain processing is a cornerstone in modern seismic processing, offering distinct advantages over time-domain methods. By dissection of seismic data into its frequency components, this approach facilitates the identification of subsurface features that may elude detection in the time domain [15]. Moreover, frequency-domain techniques elevate data quality by attenuating noise and rectifying amplitude and phase distortions introduced by the seismic acquisition system [2,17]. Furthermore, frequency-domain processing provides an efficient conduit for extracting insights from vast seismic datasets, empowering geoscientists to unravel valuable information about subsurface structures and facilitating more accurate predictions of hydrocarbon reservoir locations, sizes, and properties.

Full Waveform Inversion (FWI), a prominent exemplar of frequency-domain processing, is intimately linked with seismic modeling and extensively applied to refine the subsurface structure and property resolution [10]. Operating within the time-frequency domain, FWI enhances imaging precision by delineating subsurface structures and properties with heightened accuracy and detail [12].

In this study, we employ the NDM-net approach to seismic data in the frequency domain, emphasizing the critical role of frequency-domain processing techniques in seismic exploration and imaging. The approach revolves around computing the entire dataset for all source positions with low precision, using coarse discretization of the problem. The training dataset comprises seismograms for a few seismic sources but with high precision using sufficiently detailed discretization. Subsequently, the neural network is trained on this small training set to map high-dispersion data to accurate data. The final step involves applying the neural network to correct the entire dataset. It has been demonstrated that in the two-dimensional case, this approach can reduce the computation time for seismograms by up to seven times for a profiling observation system. In this study, the NDM-net is generalized to the three-dimensional case, and the effectiveness of the approach is illustrated using the 3D SEG/EAGE Overthrust model.

2 Statement of the Problem

Inspired by the 2D Numerical Dispersion Mitigation network (2D NDM-net) performance, we consider a similar approach in the 3D. The 3D NDM-net workflow addresses seismic modeling challenges by employing convolutional neural networks (CNNs) and constructing appropriate training datasets. Like the 2D methodology, the 3D approach employs seismic volumes derived from different source positions. This characteristic is crucial as it identifies similarities among common-shot gathers, particularly in neighboring source positions, which is fundamental for the NDM-net. Subsets of common-shot gathers are chosen to train the NDM-net to map input seismic volumes to corrected versions, reducing numerical dispersion. Initially, a small portion of the seismic volume is used for training, computed with reduced accuracy. The trained NDM-net is then applied to the entire seismic volume to mitigate numerical dispersion. Accuracy validation in 3D seismic modeling relies on numerical assessment, influenced by the training dataset selection. The proposed approach aims to expedite seismic modeling and undergo evaluation through numerical experiments.

In standard 3D land seismic surveys, the sources are typically spaced 100–300 meters apart between lines and 20–50 meters apart between sources in each line. Consequently, 3D seismic data modeling for such a system requires the computation of up to 500 seismograms per square kilometer or approximately 50,000 seismograms for the entire system covering 100 square kilometers. The variation in the seismic-geological model for adjacent source positions is relatively small, resulting in minimal differences in the corresponding seismograms for such receivers. Therefore, the main idea of the NDM-net is to calculate a complete set of seismograms using the finite difference method with discretization not exceeding 3 points per minimum wavelength. While such calculations are relatively fast, the numerical error in the resulting data is unacceptably high.

On the other hand, a small portion of the seismograms can be computed on a detailed grid with 6–10 points per wavelength. The selection of receivers for such computations can be relatively arbitrary, and several methods for selecting receivers for profile data are discussed in [5]. Subsequently, the U-net architecture neural network is trained to map high numerical dispersion data to low dispersion data. The trained network is then applied to suppress numerical dispersion for the entire dataset. To reduce the problem's dimensionality, seismograms in the time-frequency domain are used. Typically, the length of seismogram recordings is 3–5 s with a discretization from 1 to 4 ms, resulting in up to 5000 samples. Seismic modeling employs signals with a limited frequency range, so only the first 20–30% of frequencies in the Fourier transform of seismograms are significant, while the rest of the spectrum is of little interest. The demonstration of this fact was investigated in detail in [4]. In this work, we follow the same technique: we apply the Fast Fourier Transform (FFT) in time to the 3D seismic gather, cut off the spectrum of interest (typically frequencies up to 60-80 Hz), and work with this data in the frequency domain (see Fig. 1).

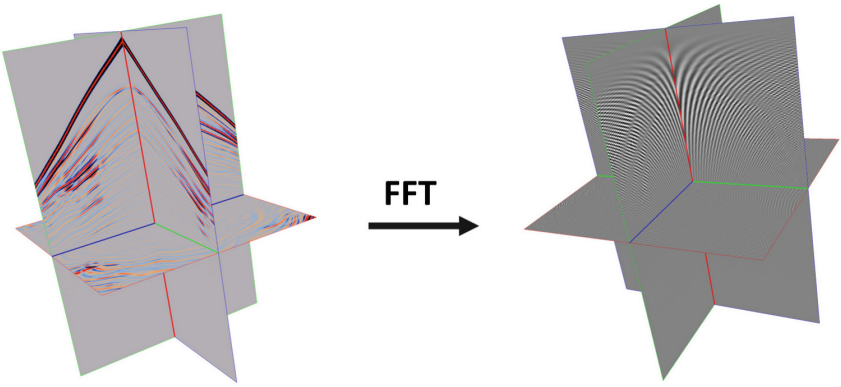


Fig. 1. The demonstration of time to frequency domain seismic data transform. The original seismogram (left), its Fourier transform (right).

2.1 3D NDM-Net in Frequency Domain

Our research suggests employing a deep neural network (DNN) to map the 3D synthetic seismogram in the frequency domain computed with a high level of numerical dispersion to the synthetic seismogram with a low level of numerical dispersion. We call this DNN the 3D Numerical Dispersion Mitigation network (3D NDM-net). The 3D NDM-net is an encoder-decoder convolutional neural network, a modified version of a 3D U-net with residual blocks (see Fig. 2). This DNN is fully convolutional, took the 3D pre-stack seismic data as input tensor with two channels for real and imaginary parts of FFT, respectively, and provided the post-processed output tensor - the 3D synthetic seismogram in the Fourier domain with a low level of numerical dispersion. The encoder section consists of five residual encoder blocks with increasing feature maps: [16, 32, 64, 128, 256]. Similarly, the decoder section comprises five decoder blocks with a subsequently decreasing number of feature maps: [256, 128, 64, 32, 16]. For the detailed technical description, see Appendix A.

3 Experimental Computations and Analysis

3.1 Model Description

The study investigates the applicability of the described approach using the 3D SEG/EAGE Overthrust acoustic velocity model (Fig. 3). This model comprehensively represents subsurface geological structures and their associated acoustic velocity variations. This high-fidelity model integrates seismic exploration data to elucidate the intricate characteristics of overthrust regions, offering insights into complex geological formations and fault structures. Through advanced computational algorithms and seismic imaging techniques, the model enables precise

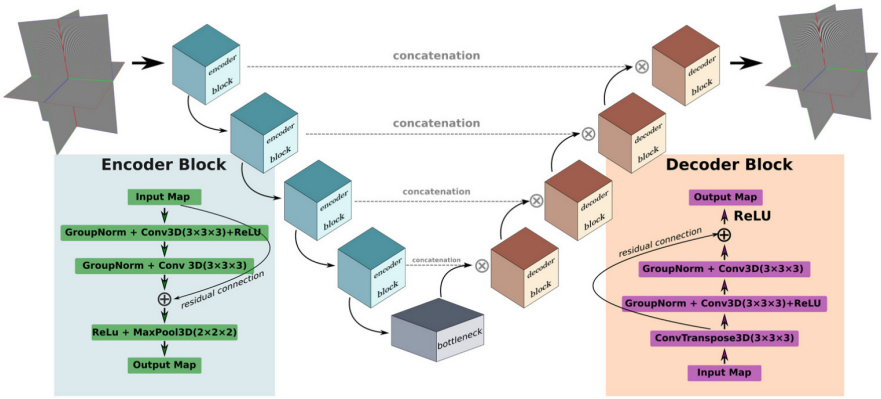


Fig. 2. The 3D synthetic seismogram in the time domain is presented on the left, and its Fourier transform (real part) is on the right.

velocity analysis and interpretation, facilitating enhanced reservoir characterization and exploration strategies in challenging overthrust terrains. With its multidimensional depiction of subsurface velocity variations, the model serves as a valuable tool for geoscientists and petroleum engineers seeking to optimize resource extraction efforts and mitigate exploration risks in overthrust geological settings.

The 3D SEG/EAGE Overthrust model has dimensions of 20×20x4.6 km with a grid spacing of 25 m in all directions. Synthetic seismograms were computed using a Ricker pulse as the source signature, with a central frequency of 20 Hz. Calculations were performed on grids with two resolutions: 25 m for the coarse grid and 12.5 m for the fine grid spacing. The observation system comprised 66 source lines spaced 150 m apart, with 25 m and 50 m spacing between receivers and sources on each line. The maximum offsets of the source-receiver pair along source lines and source cross-lines were 5 km.

3.2 Numerical Experiment 1

We decided to use the straightforward workflow in the first numerical experiment as discussed in [6]. We took a single line with index 0 (see red line in Fig. 3) and performed a numerical simulation on a fine grid for each 10-th shot position, i.e., we generated 10% equidistantly spaced training dataset. As in the 2D case, we calculate the entire set of 3D synthetic seismograms for each shot position (200 sources in a line). Following the standard NDM-net workflow, we perform 3D NDM-net training on a limited number of shot positions and then apply the trained DNN to suppress the numerical dispersion for the whole line. The

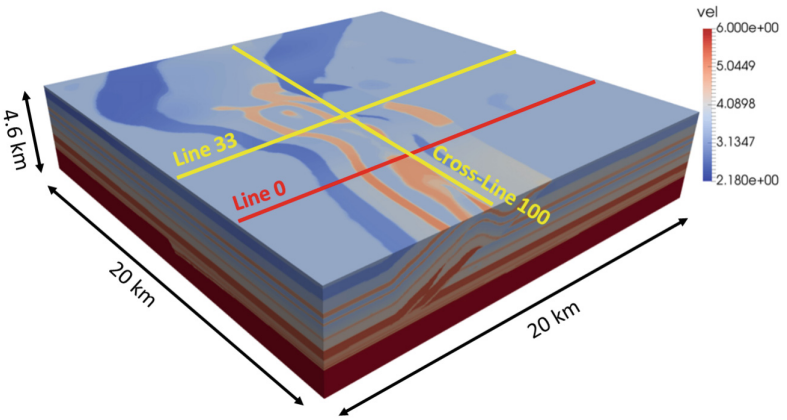


Fig. 3. The 3D SEG/EAGE Overthrust velocity model. The red line with index 0 represents the source line position for the numerical experiment 1 (see Sect. 3.2 (Color figure online)). The yellow line with index 33 and cross-line with index 100 represents the test line and cross-line position for the numerical experiment 2 described in Sect. 3.3. (Color figure online)

predicted results on a testing seismogram are presented in Fig. 4. To assess the level of numerical dispersion, we calculate the relative L2 error between the fine and coarse grid solution or its NDM-net post-processing results as a percentage (see [4]). As one may observe, the original numerical dispersion level before applying 3D NDM-net is more than 50%. After the 3D NDM-net post-processing, it is close to 11%. To demonstrate it for a whole line, we plot the numerical dispersion curves as a function of the source index (see Fig. 5). One may see that, on average, one can reduce the dispersion level up to a factor of five.

3.3 Numerical Experiment 2

The experiment 1 demonstrates, that as in the 2D case we can process the 3D data line-by-line by generating 10% equidistantly spaced training datasets with the subsequent 3D NDM-net training and post-processing. In other words, we still need to generate 10% seismograms of the whole acquisition system using a fine numerical grid. But what if we upscale our idea on the cross-line direction? This means that we totally generate just 1% of fine grid solutions and potentially reach even better speed-up. To follow in this direction, in this numerical experiment we choose only 1% of the entire set of source positions. We randomly choose the 1% of uniformly distributed source positions for simulating the fine grid solutions (blue dots in Fig. 6). As in the experiment one we still need to calculate the entire set of sources using the coarse numerical grid. For testing

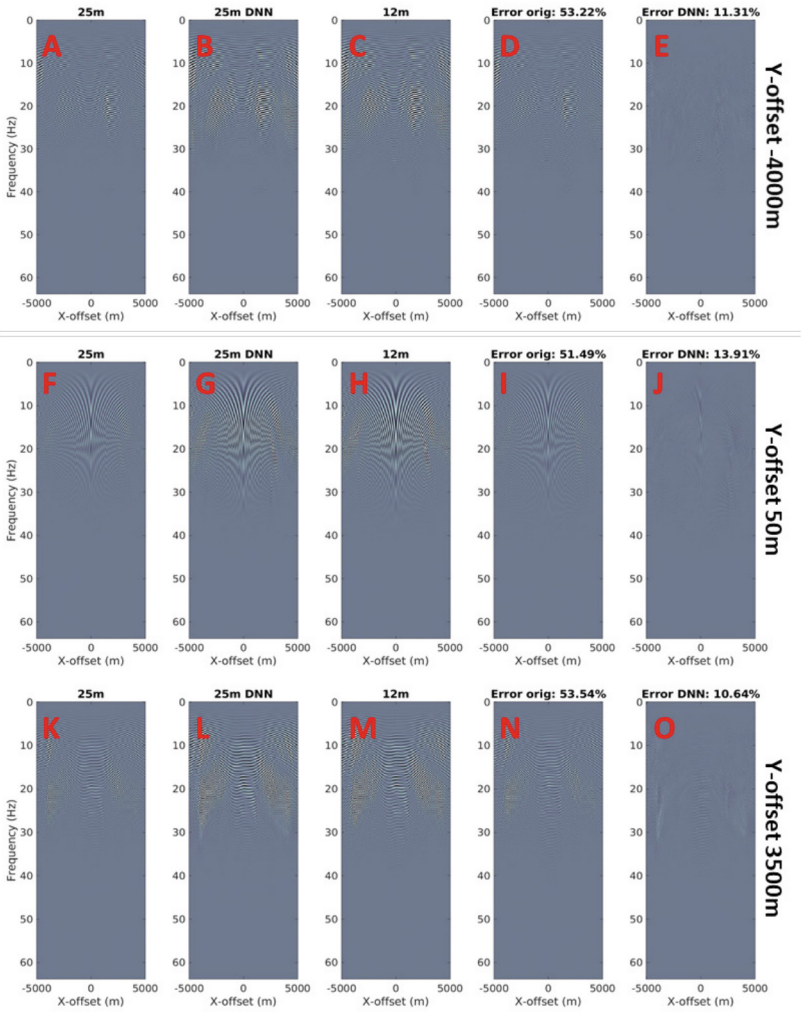


Fig. 4. The testing results in the frequency domain (real part of the FFT) for numerical experiment 1. The 3D synthetic data is presented as 2D slices for a different Y-offset value: plots (A), (B), (C), (D), (E) for offset = –4000 m, plots (F), (G), (H), (I), (J) for offset = 50 m and plots (K), (L), (M), (N), (O) for offset = 3500 m. From the left to the right: the data on the coarse grid (plots (A), (F), (K)), the 3D NDM-net postprocessing results (plots (B), (G), (L)), the fine grid data (plots (C), (H), (M)), the difference between the coarse and fine grid solutions (plots (D), (I), (N)), and the difference between fine grids solution and 3D NDM-net postprocessing results (plots (E), (J), (O)). All data are plotted using the same colorbar.

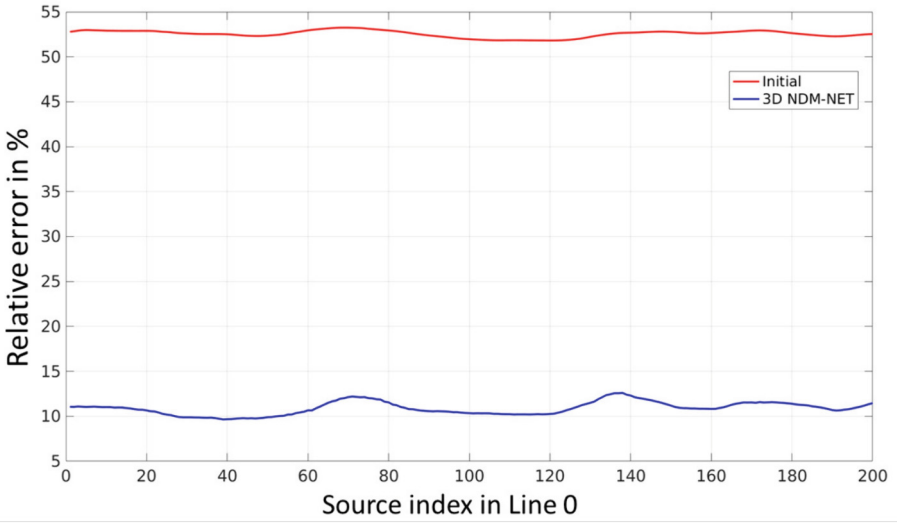


Fig. 5. The numerical dispersion curves. The red plot is a relative error in percentage between the coarse and fine grid solutions (original numerical dispersion level) as a function of a source index. Similarly, the blue plot shows the level of numerical dispersion after the 3D NDM-net postprocessing. (Color figure online)

we choose the middle line with index 33 and the corresponding middle cross-line index 100 (red dots in Fig. 6). The testing gather prediction results are demonstrated in Fig. 7. Compared to the experiment 1, in this experiment we achieve a higher level of numerical dispersion. But this level is still acceptable from the seismic processing point of view. On the other hand, we greatly save the time for generating the seismic data - one need to calculate just 1% of fine grid solutions, as opposed to 10% in the experiment 1. Figure 8 shows the numerical dispersion curves for line 33 and cross-line 100. As we see, in average we are able to reduce the numerical dispersion level up the factor 3.

The computation time for one seismic source on the coarse grid was approximately 12 min on a dual Intex Xeon CPU node. Computing the solution on the fine grid required about 195 min on the same node. Thus, computing the complete dataset on the coarse grid took around 2,600 h; on the fine grid, it took about 43,000 h. Training on 1% of the data took 4 h on a single NVidia RTX3090Ti GPU, while applying the NDM-net took less than 1 min per seismic record, i.e., less than 220 h for a whole dataset. Combining the computational time on a coarse grid with the 3D NDM-net training and post-processing time, we achieved a speed-up factor of about 15.

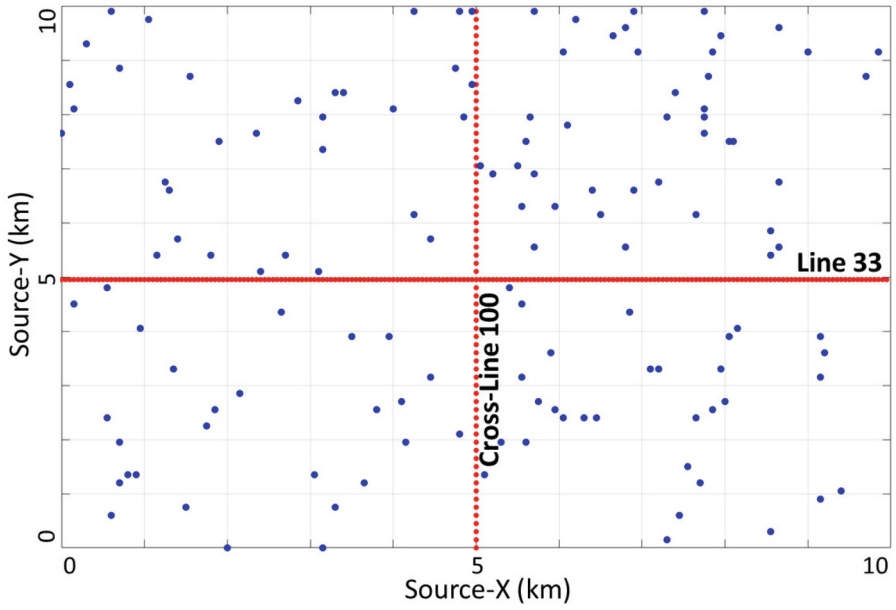


Fig. 6. The random uniformly distributed 1% of the source positions (blue dots) for generating the training dataset, and the testing source positions (red dots) for line index 33 and cross-line index 100. (Color figure online)

4 Conclusion

The paper presents an innovative method for 3D seismic modeling. This approach integrates classical grid-based methods, notably finite difference methods, with machine learning techniques to mitigate numerical dispersion and rectify data. The study demonstrates that in a three-dimensional setting, particularly in modeling data for modern 3D land acquisition systems, the proposed approach significantly reduces computation time by over an order of magnitude.

A 3D NDM-Net Technical Description

The extended description of the 3D Residual U-Net (3D NDM-net) architecture, illustrated in Fig. 2, is presented in this Appendix.

Encoder Architecture

The encoder section consists of five encoder blocks. Each block consists of 3D convolutions, ReLu [3], max poolings and group normalization operators [14]. In each encoding block, the residual connection summarises the output of Conv1 and Conv3. At the block's end, ReLU activation and MaxPooling with a kernel size of $2 \times 2 \times 2$ are applied.

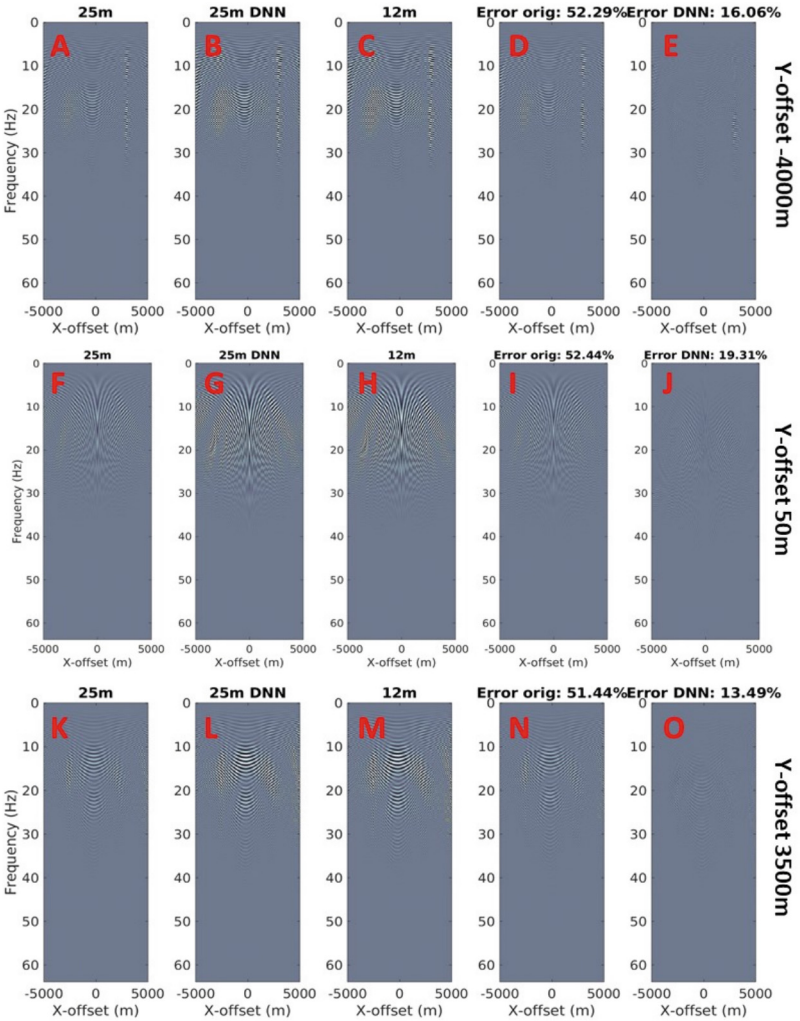


Fig. 7. The testing results in the frequency domain (real part of the FFT) for numerical experiment 2. The 3D synthetic data is presented as 2D slices for a different Y-offset value: plots (A), (B), (C), (D), (E) for offset = –4000 m, plots (F), (G), (H), (I), (J) for offset = 50 m and plots (K), (L), (M), (N), (O) for offset = 3500 m. From the left to the right: the data on the coarse grid (plots (A), (F), (K)), the 3D NDM-net postprocessing results (plots (B), (G), (L)), the fine grid data (plots (C), (H), (M)), the difference between the coarse and fine grid solutions (plots (D), (I), (N)), and the difference between fine grids solution and 3D NDM-net postprocessing results (plots (E), (J), (O)). All data are plotted using the same colorbar.

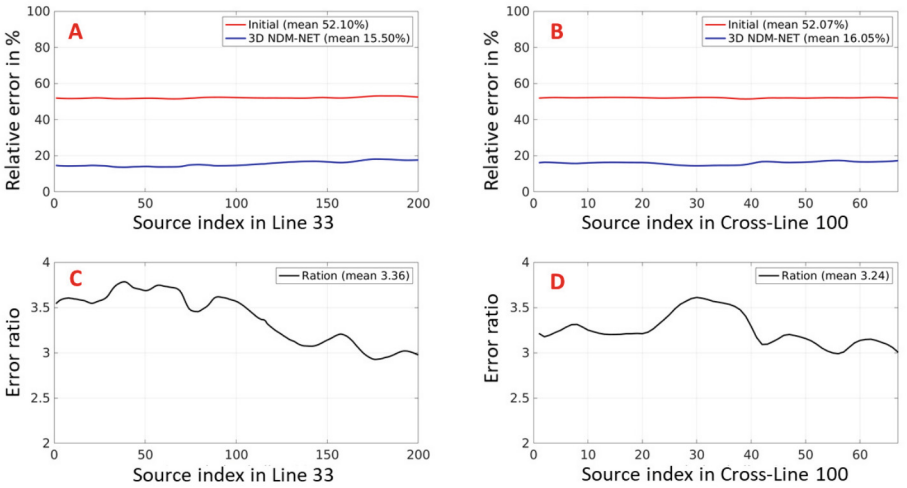


Fig. 8. The numerical dispersion curves. Plots (A) and (C) are results for testing line 33, and plots (B) and (D) are for testing cross-line 100. The red plot is the original numerical dispersion (relative error as a percentage) as the function of the source index. In contrast, the blue plot is the suppressed numerical dispersion after the 3D NDM-net postprocessing. The ratio between the original and suppressed numerical dispersion levels is plotted in black as a function of the source index. (Color figure online)

Block 1

1. Conv1: $1 \times 1 \times 1$ Conv3d with 2 input channel (for real and imaginary parts of the input seismogram) and 16 output channels.
2. Conv2: $3 \times 3 \times 3$ Conv3d with 16 input channels, outputting 16 feature maps, using GroupNorm, and ReLU activation.
3. Conv3: $3 \times 3 \times 3$ Conv3d with 16 input channels, outputting 16 feature maps, and employing GroupNorm.
4. ResidualConnect: Output of Conv1 and Conv3 are summarised, ReLu activation, and MaxPool3D is applied.

Block 2

1. Conv1: $1 \times 1 \times 1$ Conv3d with 16 input channels and 32 output channels.
2. Conv2: $3 \times 3 \times 3$ Conv3d with 32 input channels, outputting 32 feature maps, using GroupNorm, and ReLU activation.
3. Conv3: $3 \times 3 \times 3$ Conv3d with 32 input channels, outputting 32 feature maps, and employing GroupNorm.
4. ResidualConnect: Output of Conv1 and Conv3 are summarised, ReLu activation, and MaxPool3D is applied.

Block 3

1. Conv1: $1 \times 1 \times 1$ Conv3d with 32 input channels and 64 output channels.
2. Conv2: $3 \times 3 \times 3$ Conv3d with 64 input channels, outputting 64 feature maps, using GroupNorm, and ReLU activation.
3. Conv3: $3 \times 3 \times 3$ Conv3d with 64 input channels, outputting 64 feature maps, and employing GroupNorm.
4. ResidualConnect: Output of Conv1 and Conv3 are summarised, ReLu activation, and MaxPool3D is applied.

Block 4

1. Conv1: $1 \times 1 \times 1$ Conv3d with 64 input channels and 128 output channels.
2. Conv2: $3 \times 3 \times 3$ Conv3d with 128 input channels, outputting 128 feature maps, using GroupNorm, and ReLU activation.
3. Conv3: $3 \times 3 \times 3$ Conv3d with 128 input channels, outputting 128 feature maps, and employing GroupNorm.
4. ResidualConnect: Output of Conv1 and Conv3 are summarised, ReLu activation, and MaxPool3D is applied.

Block 5

1. Conv1: $1 \times 1 \times 1$ Conv3d with 128 input channels and 256 output channels.
2. Conv2: $3 \times 3 \times 3$ Conv3d with 256 input channels, outputting 256 feature maps, using GroupNorm, and ReLU activation.
3. Conv3: $3 \times 3 \times 3$ Conv3d with 256 input channels, outputting 256 feature maps, and employing GroupNorm.
4. ResidualConnect: Output of Conv1 and Conv3 are summarised, ReLu activation, and MaxPool3D is applied.

Decoder Architecture

The decoder section comprises four decoder blocks. The input to each decoder block is concatenated with the corresponding encoder block (skip connections, see Fig. 2 for visual representation. Each block initially contains an upsampling layer, followed by 3D convolutions, group normalization, and ReLU activations. In each decoding block, the residual connection summarises the output of TransposeConv and Conv2. At the block's end, ReLU activation is applied.

Block 1

1. TransposeConv: $3 \times 3 \times 3$ ConvTranspose3d for upsampling.
2. Conv1: $3 \times 3 \times 3$ Conv3d with 128 input channels and 128 output channels, using GroupNorm and ReLU activation.
3. Conv2: $3 \times 3 \times 3$ Conv3d with 128 input channels and 128 output channels, employing GroupNorm.
4. ResidualConnect: Output of TransposeConv and Conv2 are summarised, ReLu activation is applied.

Block 2

1. TransposeConv: $3 \times 3 \times 3$ ConvTranspose3d for upsampling.
2. Conv1: $3 \times 3 \times 3$ Conv3d with 128 input channels and 64 output channels, using GroupNorm and ReLU activation.
3. Conv2: $3 \times 3 \times 3$ Conv3d with 64 input channels and 64 output channels, employing GroupNorm.
4. ResidualConnect: Output of TransposeConv and Conv2 are summarised, ReLu activation is applied.

Block 3

1. TransposeConv: $3 \times 3 \times 3$ ConvTranspose3d for upsampling.
2. Conv1: $3 \times 3 \times 3$ Conv3d with 64 input channels and 32 output channels, using GroupNorm and ReLU activation.
3. Conv2: $3 \times 3 \times 3$ Conv3d with 32 input channels and 32 output channels, employing GroupNorm.
4. ResidualConnect: Output of TransposeConv and Conv2 are summarised, ReLu activation is applied.

Block 4

1. TransposeConv: $3 \times 3 \times 3$ ConvTranspose3d for upsampling.
2. Conv1: $3 \times 3 \times 3$ Conv3d with 32 input channels and 16 output channels, using GroupNorm and ReLU activation.
3. Conv2: $3 \times 3 \times 3$ Conv3d with 16 input channels and 16 output channels, employing GroupNorm.
4. ResidualConnect: Output of TransposeConv and Conv2 are summarised, ReLu activation is applied.

The final layer is a 1×1v1 Conv3d layer with 16 input channels and 2 output channels, for real and imaginary part of enhanced seismogram in the frequency domain.

References

1. Ainsworth, M.: Discrete dispersion relation for hp-version finite element approximation at high wave number. SIAM J. Numer. Anal. **42**(2), 553–575 (2004)
2. Elboth, T., Geoteam, F., Qaisrani, H.H., Hertweck, T.: De-noising seismic data in the time-frequency domain. SEG Expanded Abstracts, pp. 2622–2626 (2008)
3. Fukushima, K.: Visual feature extraction by a multilayered network of analog threshold elements. IEEE Trans. Syst. Sci. Cybern. **5**(4), 322–333 (1969). https://doi.org/10.1109/TSSC.1969.300225
4. Gadylshin, K., Lisitsa, V.V., Gadylshina, K., Vishnevsky, D.M.: Frequency domain numerical dispersion mitigation network. In: Gervasi, O., et al. (eds.) Computational Science and Its Applications - ICCSA 2023 Workshops - Athens, Greece, July 3-6, 2023, Proceedings, Part III. LNCS, vol. 14106, pp. 31–44. Springer (2023). https://doi.org/10.1007/978-3-031-37111-0_3

5. Gadylshin, K., Lisitsa, V.V., Vishnevsky, D.M., Gadylshina, K.: Hausdorff-distance-based training dataset construction for numerical dispersion mitigation neural network. Comput. Geosci. **180**, 105438 (2023). https://doi.org/10.1016/J.CAGEO.2023.105438
6. Gadylshin, K., Vishnevsky, D., Gadylshina, K., Lisitsa, V.: Numerical dispersion mitigation neural network for seismic modeling. Geophysics **87**(3), T237–T249 (2022)
7. Goodfellow, I.J., Bengio, Y., Courville, A.: Deep Learning. MIT Press, Cambridge, MA, USA (2016). http://www.deeplearningbook.org
8. Kaur, H., Fomel, S., Pham, N.: Overcoming numerical dispersion of finite-difference wave extrapolation using deep learning. In: SEG Technical Program Expanded Abstracts, pp. 2318–2322 (2019). https://doi.org/10.1190/segam2019-3207486.1
9. Lisitsa, V.: Dispersion analysis of discontinuous galerkin method on triangular mesh for elastic wave equation. Appli. Math. Model. **40**, 5077–5095 (2016). https://doi.org/10.1016/j.apm.2015.12.039
10. Pratt, R.G., Shin, C., Hick, G.J.: Gauss-Newton and full Newton methods in frequency-space seismic waveform inversion. Geophys. J. Inter. **133**(2), 341–362 (1998)
11. Siahkoohi, A., Louboutin, M., Herrmann, F.J.: The importance of transfer learning in seismic modeling and imaging. Geophysics **84**, A47–A52 (2019). https://doi.org/10.1190/geo2019-0056.1
12. Tcheverda, V., Gadylshin, K.: Elastic full-waveform inversion using migration-based depth reflector representation in the data domain. Geosciences **11**(2) (2021)
13. Virieux, J., Calandra, H., Plessix, R.E.: A review of the spectral, pseudo-spectral, finite-difference and finite-element modelling techniques for geophysical imaging. Geophys. Prospect. **59**(5), 794–813 (2011). https://doi.org/10.1111/j.1365-2478.2011.00967.x
14. Wu, Y., He, K.: Group normalization (2018)
15. Yilmaz, Ö., Doherty, S.: Seismic Data Analysis: Processing, Inversion, and Interpretation of Seismic Data. No. 10,v. 1 in Crisp Fifty-Minute Books, Society of Exploration Geophysicists (2001)
16. Yu, S., Ma, J.: Deep learning for geophysics: Current and future trends. Rev. Geophys. **59**(3), e2021RG000742 (2021)
17. Zhao, Y., Liu, Y., Li, X., Jiang, N.: Time-frequency domain snr estimation and its application in seismic data processing. J. Appl. Geophys. **107**, 25–35 (2014)

Dependence of CO_2 Breakthrough on the Sorbent Packing

Alexandra Gonchar[1], Vadim Lisitsa[2(✉)], Tatyana Khachkova[2], Dmitry Prokhorov[3], and Vladimir Derevschikov[3]

[1] Novosibirsk State University, Pirogova Street 2, 630090 Novosibirsk, Russia
[2] Institute of Petroleum Geology and Geophysics SB RAS, Koptug Avenue 3, 630090 Novosibirsk, Russia
lisitsavv@ipgg.sbras.ru
[3] Institute of Mathematics SB RAS, Koptug Avenue 4, 630090 Novosibirsk, Russia

Abstract. In this paper, we present a numerical study of the effect of the bulk sorbent particle packing on the break-through time. In our experiments, we fix the physical and chemical properties of the sorbent particles but vary the packing density (macroporosity) and the CO_2 volume fraction at the inlet. After that, the gas flow through the reactor is simulated, and CO_2 volume fraction as a function of time at the outlet is measured. We show that, in the case of high macroporosity, the recorded CO_2 concentration strongly depends on the macroporosity. On the contrary, if the macroporosity is low, we observe almost no difference in the break-through curves for the models with macroporosity less than 45%.

Keywords: Chemosorption · reactive transport · finite differences

1 Introduction

Carbon dioxide chemosorption is an important technology with several applications, such as fire safety and mine rescue equipment, inhalation anesthesia, respiratory care and others. The CO_2 sorbers are commonly based on the soda-lime porous sorbents, which supply the following chemical reaction $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 \downarrow + H_2O$. Soda-lime sorbents are solid porous particles that are packed inside a reactor. The bulk sorbents' efficiency depends on the sorbent particles' physical and chemical properties, such as porosity, formation factor, efficient diffusion, chemical reaction rate, initial $Ca(OH)_2$ concentration, and others. However, bulk sorbents may have different packing densities, affecting the gas flow and advective transport of CO_2 in the inter-particle space.

In our previous research [10], we presented the numerical algorithm for direct computational fluid dynamics simulation of gas flow in the reactor filled with the bulk sorbent and further CO_2 transport and chemosorption by the sorbent particles. We paid primary attention to the properties of the sorbent, i.e.,

The research was supported by the Russian Science Foundation grant no. 21–71-20003.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 290–304, 2024.
https://doi.org/10.1007/978-3-031-65238-7_20

porosity, effective diffusion, and reaction rate. In particular, we simulated CO_2 sorption by a single particle and investigated the chemical compound of the particle at different time instants. Numerical simulations were compared over the lab measurements, which let us calibrate the mathematical model. In particular, we estimated the formation factor and chemical reaction rates for Loflosorb particles [2].

However, particle packing density may also affect the efficiency of CO_2 sorption due to differences in the inter-particle space geometry, which may affect the CO_2 transport. This paper presents a numerical study of the packing density on the break-through curves (dependence on CO_2 concentration at the outlet on time). We generated several statistical realizations of spherical particle packing for four different packing densities (macro-porosity values). After that, we simulated the advection-diffusion reaction process inside the reactor and recorded CO_2 concentration at the outlet to investigate how strong the relation between the bulk sorbent packing density and the efficiency of CO_2 sorption.

2 Mathematical Problem Formulation

We assume the model has two types of pores. The reciprocal positions of the sorbent particles form the macropores. This type of pore space is the main objective of current research. Macropores support both the advection and the diffusion of CO_2. The second type of pores are the micropores inside the sorbent particles. The particular sorbent defines this pore space and can not be changed during the experiments. We assume that only the diffusion of CO_2 is allowed in micropores and no advection.

We introduce the domain D, where the chemosorption process is considered. This domain is a union of two non-overlapping subdomains D_p and D_g, which are the macro- and microporous spaces, respectively. Sketches of the computational domains for two different sorbent packs are presented in Fig. 1.

We assume that the fluid flow is allowed inside the macropores D_p. To simplify further considerations, the fluid is assumed to be incompressible; moreover, the chemosorption process is slow, with no changes in model geometry. Thus, we may deal with the steady-state flow satisfying the steady-state Stokes equation in D_p:

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

On the contrary, no flow is allowed in the micropores D_g, thus

$$\vec{u} = 0. \tag{2}$$

In this notation, $p(\vec{x})$ is the fluid pressure, $\vec{u}(\vec{x})$ is the fluid flow velocity, and μ is the dynamic viscosity of the fluid.

We need to state the boundary conditions to resolve the fluid flow inside the macropores. Let us consider several types of boundaries. First, the interfaces between the macroporous space, the sorbent particles, and the sides of the reactor (Fig. 2). We pose the no flow conditions at these interfaces Γ:

$$\vec{u} = 0. \tag{3}$$

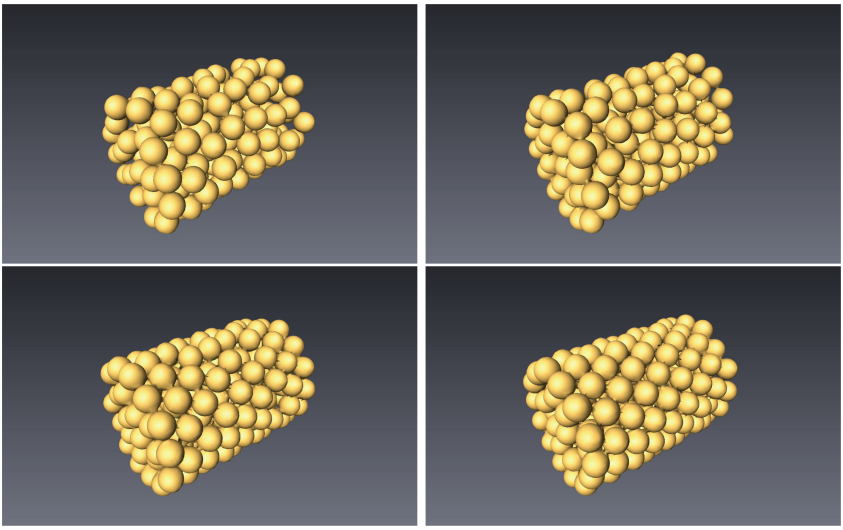


Fig. 1. Sketches of the computational domains. The Interior of the spherical particles corresponds to the microporous space D_g, and the exterior corresponds to D_p. The porosity of the left top model is 55%, porosity of the right top model is 50%, porosity of the left bottom model is 45%, and porosity of the right bottom model is 40%.

Second boundary type is the inlet Γ_{in} defied as $x_1 = x_1^{in}$, where flow rate is defined according to the formula:

$$Q(x_1^{in}) = \int_{x_2,x_3} v_1(x_1^{in}, x_2, x_3) dx_2 dx_3 = Q_{in}. \tag{4}$$

Third boundary type is the outlet Γ_{out} defied as $x_1 = x_1^{out}$, where the pressure is fixed:

$$p(x_1^{out}) = p^{out}. \tag{5}$$

The equation governing the reactive transport can be stated inside the entire computational domain $D = D_g \cup D_p$:

$$\frac{\partial}{\partial t}(\phi C_j) + \nabla \cdot (\vec{u} C_j) - \nabla \cdot (D_j \nabla C_j) = g_j(\vec{C}). \tag{6}$$

In these notations, C_j represents the molar concentration of chemical species, D_j is the diffusion coefficient of the particular species, ϕ is the open porosity of the microporous material, functions $g_j(\vec{C})$ are defined by the chemical reactions. It is clear that for the macropores, porosity equals one ($\phi = 1$) and $\vec{u}(\vec{x})$ is the flow velocity which is the solution of Stokes equation (1), and the diffusion coefficients D_j correspond to molecular diffusion of the particular species; i.e., $D_j = D_j^0$. On the contrary, in the microporous space, the porosity is less than one ($\phi < 1$), the flow rate is zero ($\vec{u} = 0$), and the diffusion coefficient is reduced

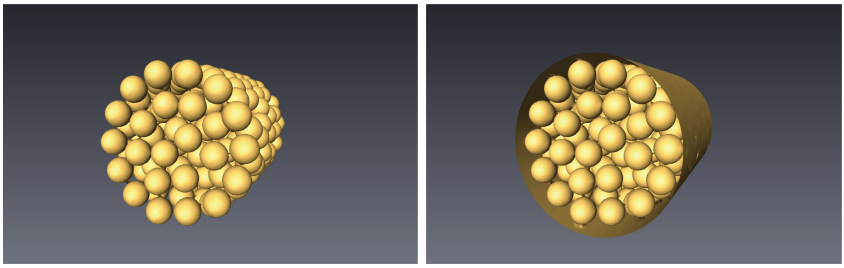


Fig. 2. Sketches of the computational domains without the reactor sides (left) and with the reactor (right).

according to the estimate $D_j = \phi D_j^0 / F$, where F is the formation factor [6]. For most porous materials, the formation factor is bounded as $F \in [1, 10]$.

In this paper, we simulate the CO_2 chemosorption by the soda-lime sorbent, which satisfy the following reaction equation:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O. \tag{7}$$

Among these species, CO_2 and H_2O are movable. Thus, their transport satisfies the advection-diffusion-reaction equation (6), whereas $Ca(OH)_2$ and $CaCO_3$ are immovable, their concentrations change only due to the chemical reaction.

The advection-diffusion-reaction system requires the initial conditions for all species and boundary conditions for movable species. The initial conditions are

$$\begin{aligned} &C_j(\vec{x}, 0) = 0, \quad \vec{x} \in D_p,\ i = 1, ..., J; \\ &C_m(\vec{x}, 0) = 0, \quad \vec{x} \in D_g,\ m = 1, ..., M; \\ &C_i(\vec{x}, 0) = C_i^0,\ \vec{x} \in D_g,\ i = M+1, ..., J \end{aligned}$$

where, following [10], C_j corresponds to all considered species, C_m, $m = 1, ..., M$ represents the movable species, and C_i, $i = m+1, ..., J$ corresponds to immovable species. The presented initial conditions set concentrations of all species to zero in the macropores. Movable species are not present in the microporous space either. On the contrary, immovable species are defined as nontrivial inside the sorbent particles.

We also need to state the boundary conditions for the movable species. They are

$$\begin{aligned} &C_m(x_1^{in}, t) = C_m^{in},\ \vec{x} \in x_1^{in} \quad m = 1, ..., M; \\ &\tfrac{\partial C_m}{\partial \vec{n}}(\vec{x}, t) = 0, \qquad \vec{x} \in x_1^{out}\ m = 1, ..., M. \\ &\tfrac{\partial C_m}{\partial \vec{n}}(\vec{x}, t) = 0, \qquad \vec{x} \in \Gamma_{ext}\ m = 1, ..., M. \end{aligned}$$

The first set of conditions defines the concentrations of movable species at the inlet. The second set of conditions is defined at the outlet, stating the free flow condition. The last set of equations is stated at the sides of the reactor, and they guarantee that no external factors affect the concentrations at this surface. Note that the advection-diffusion-reaction equations are stated inside the entire

computational domain; thus, no explicit conditions are required at the interface between the macropores and sorbent particles.

We also need to specify the reactive part of the Eq. (6). Chemosorption of CO_2 by soda-lime sorbent satisfy the reaction (7) with the following kinetics:

$$\begin{array}{c} \frac{\partial}{\partial t}\left(\phi C_{CO_2}\right) + \nabla \cdot \left(\vec{u} C_{CO_2}\right) - \nabla \cdot \left(D_{CO_2} \nabla C_{CO_2}\right) = -k\phi C_{CO_2} C_{Ca(OH)_2}, \\ \frac{\partial}{\partial t}\left(\phi C_{H_2O}\right) + \nabla \cdot \left(\vec{u} C_{H_2O}\right) - \nabla \cdot \left(D_{H_2O} \nabla C_{H_2O}\right) = k\phi C_{CO_2} C_{Ca(OH)_2}, \\ \frac{\partial}{\partial t}\left(C_{Ca(OH)_2}\right) = -k\phi C_{CO_2} C_{Ca(OH)_2}, \\ \frac{\partial}{\partial t}\left(C_{CaCO_3}\right) = k\phi C_{CO_2} C_{Ca(OH)_2}, \end{array} \tag{8}$$

Note that the considered reactions are irreversible, and the concentration of the species products does not depend on the concentration of the products, i.e., C_{H_2O} and C_{CaCO_3}. Moreover, transport of CO_2 does not depend on water or $CaCO_3$ concentration; thus, these two species may be excluded from the considerations. In our previous research [10], we computed the $CaCO_3$ concentration to compare the simulation results with the lab experiments. However, such data is unavailable for the break-through experiments.

The reduced system of advection-diffusion-reaction system can be represented as

$$\begin{array}{c} \frac{\partial}{\partial t}\left(\phi C_{CO_2}\right) + \nabla \cdot \left(\vec{u} C_{CO_2}\right) - \nabla \cdot \left(D_{CO_2} \nabla C_{CO_2}\right) = -k\phi C_{CO_2} C_{Ca(OH)_2}, \\ \frac{\partial}{\partial t}\left(C_{Ca(OH)_2}\right) = -k\phi C_{CO_2} C_{Ca(OH)_2}, \end{array} \tag{9}$$

with the following boundary and initial conditions:

$$\begin{array}{ll} C_{CO_2} = C^{in}_{CO_2}, & \vec{x} \in x^{in}_1 \\ \frac{\partial C_{CO_2}}{\partial \vec{n}} = 0, & \vec{x} \in x^{out}_1 \\ \frac{\partial C_{CO_2}}{\partial \vec{n}} = 0, & \vec{x} \in \Gamma_{ext} \end{array} \tag{10}$$

$$\begin{array}{ll} C_{CO_2}(0, \vec{x}) = 0, & \vec{x} \in D_p \cup D_g, \\ C_{Ca(OH)_2}(0, \vec{x}) = 0, & \vec{x} \in D_p, \\ C_{Ca(OH)_2}(0, \vec{x}) = C^0_{Ca(OH)_2}, & \vec{x} \in D_g, \end{array} \tag{11}$$

3 Numerical Methods

Numerical methods and implemented numerical algorithms to solve the considered problem in models with irregular interfaces are discussed in detail in [10]. Here, we briefly remind the main aspects.

In this research, we use finite differences on regular rectangular (cubic) grids to approximate the Stokes and advection-diffusion-reaction equations. Thus, we need to apply special techniques to account for the sorbent particles' spherical form and the reactor's cylindrical form. It can be efficiently done using the level-set method [4,9,14,16] in combination with the immersed boundaries method [5,8,9,13]. Moreover, two level-sets $\varphi^p(\vec{x})$ and $\varphi^e(\vec{x})$ are defined to distinguish the interfaces between the macroporous and microporous domains and between the interior and exterior of the reactor, respectively. The two interfaces are equivalent

for the fluid flow solver because they are impermeable to the fluid flow. However, the two types of interfaces are treated differently when the advection-diffusion-reaction equation is solved.

The approximation of Stokes equation is based on the second-order accurate finite differences on staggered grids. The pressure is defined in integer points, whereas the velocity components are stored at the points with one half-integer index; for example, u_1 is defined in points $((x_1)_{i+1/2}, (x_2)_j, (x_3)_k)$. Note that Stokes equation is approximated only in macropores, thus for $\varphi^p(\vec{x}) > 0$ and $\varphi^e(\vec{x}) > 0$. The projection-type methods are used to solve an obtained system of linear algebraic equations, where the Krylov-type methods treat the Poisson equation with spectral preconditioner [7].

Advection-diffusion-reaction equations are solved with the operator splitting technique. We apply the AD-R splitting scheme, where the prediction step is applied to solve the coupled advection-diffusion part of the equation, and then the correction is performed to account for the reaction. The advection term is approximated using the third-order WENO scheme [11,16,17], whereas the diffusion part is approximated with the second-order central differences [7].

Approximation of the reactive part is based on the implicit time stepping scheme, which is unconditionally stable, but the time step is used to preserve the desired accuracy level. The details of the approximation are provided in [10].

4 Model Construction

To generate the model of the reactor filled with the spherical sorbent particles with required porosity we used Lubachevsky-Stillinger algorithm [12] as in [1].

The Lubachevsky-Stillinger algorithm simulates motion and interaction of elastic spherical particles with increasing radius. At the beginning of the simulation the spheres have zero radii, random positions and velocities. The algorithm implements event-based approach. Therefore, it consists of two main parts: computation of interaction time and velocities recalculation. In case of particle-particle interaction both parts are described in [12] (2D) and [15] (3D). However, the usual domain for packing by Lubachevsky-Stillinger is a rectangle with periodic boundary, which differs from current case: cylinder with impenetrable boundary. Thus, in this section we describe our approach to particle-boundary interactions.

Let us assume a cylinder in $\mathbb{R}^3$ with radius R and height H, whose height coincides with Z-axis from 0 to H. The state of the particle is defined by seven parameters (x, y, z) — coordinate of the center, (v_x, v_y, v_z) — velocity vector, r — radius. The initial arrangement is chosen randomly:

$$\begin{aligned} x &= R\sqrt{r_u}\cos\phi, & v_x &= \sqrt{1-(2u-1)^2}\cos\theta, \\ y &= R\sqrt{r_u}\sin\phi, & v_y &= \sqrt{1-(2u-1)^2}\sin\theta, \\ z &= Hh_u, & v_z &= 2u-1, \\ r &= 0, \end{aligned}$$

where u, h_u, r_u are random variables with uniform distribution on the segment $[0, 1]$, ϕ and θ are random variables with uniform distribution on the segment $[0, 2\pi]$. The radius growth rate is assumed to be linear $r = at$.

The interaction time with the bottom base of the cylinder can be computed by the formula:

$$t_i = t_c + \frac{z - at_c}{a - v_z},$$

where t_c is the current time. Similarly, interaction time with the top base is:

$$t_i = t_c + \frac{H - z - at_c}{a + v_z}.$$

The interaction time with the side is t_c plus the minimal positive value of the equation:

$$\begin{aligned} &At^2 + 2Bt + C = 0, \\ &A = v_x^2 + v_y^2 - a^2, \\ &B = xv_x + yv_y + a(R - at_c), \\ &C = x^2 + y^2 - (R - at_x)^2. \end{aligned}$$

To avoid the intersection of the growing sphere with the boundary, we increase the velocity after the interaction, so in the case of cylinder bases, this leads to the following expression for velocities:

$$\begin{aligned} v_x^{new} &= v_x \\ v_y^{new} &= v_y \\ v_z^{new} &= \pm(|v_z| + 1.1a), \end{aligned}$$

where $+$ sign corresponds to bottom base, $-$ to top base. However, on a side with negative curvature, the velocity increase may be large if the angle of particle incidence is acute. High velocities cause small intervals between steps [12], so for simplicity, we reflect particles perpendicular to side:

$$\begin{aligned} v_x^{new} &= -\frac{x(\sqrt{v_x^2 + v_y^2} + 1.1a)}{\sqrt{x^2 + y^2}}, \\ v_y^{new} &= -\frac{y(\sqrt{v_x^2 + v_y^2} + 1.1a)}{\sqrt{x^2 + y^2}}, \\ v_z^{new} &= v_z. \end{aligned}$$

The algorithm takes as input H, R, r_s (radius of sorbent particles), ρ (dimensionless density), computes required number of particles $N = \frac{3\rho HR^2}{4r_s^3}$, creates random initial configuration and performs iterations until $r = r_s$.

5 Numerical Experiments

To perform the numerical experiments estimating the breakthrough time in dependence on the packing density, we considered a cylindrical reactor with a diameter of 17 mm and a length of 24 mm. It was filled with spherical sorbent particles 3 mm in diameter. We simulated the breakthrough process for the Soda-lime Loflosorb (Intersurgical Ltd, UK). This commercially available CO_2 sorbent is used in breathing systems to absorb exhaled carbon dioxide during anesthesia. Note that in the previous research [10], we calibrate the mathematical model to match this sorbent's formation factor and reaction rate. Loflosorb contains 60 wt% of $Ca(OH)_2$, 15 wt% of water, and less than 0.1 wt% of the indicator (ethyl violet) [3]. The mass density of the granules, porosity (measured in m^3/kg), and mass fraction of H_2O, $Ca(OH)_2$, and $CaCO_3$ at the initial stage were measured in a lab. They are provided in Table 1, as well as an estimation of the formation factor and the chemical reaction rate. In particular, we focused on the experiments with a fixed form factor equal to 5 and a reaction rate equal to 10^{-3}. The material's dimensionless porosity equals 0.49 as follows from computations, presented in [10]. Note that all provided parameters characterize the sorbent and can not be changed in a lab.

Table 1. Measured properties of the sorbent at the initial stage.

property	notation	Loflosorb
density (kg/m^3)	ρ	1080
chem. porosity (m^3/kg)	v_p	$4.6 \cdot 10^{-4}$
mass fraction of $Ca(OH)_2$	$\mu_{Ca(OH)_2}$	0.76
mass fraction of $CaCO_3$	μ_{CaCO_3}	0.05
Form factor	F	5–9
reaction rate	k	$10^{-3} - 10^{-2}$

On the contrary, the variable parameters in the breakthrough experiments are the density of the particle packing and CO_2 concentration at the inlet. To reduce the number of simulations, we focused only on the rapid flows corresponding to 15 liters per hour flow rates or $4.14 \cdot 10^{-6}$ m^3/s. We considered three values of CO_2 concentration at the inlet equal to 1, 5, and 7% of volumetric concentration. We also considered four different values of particle packing density characterized by the macroporosity (ratio of the volume of macropores to the volume of the entire reactor), which was 40, 45, 50, and 55 %. Note that the reactor diameter is about five diameters of the particles; achieving smaller porosity (denser packing) is impossible due to the side effects. Examples of different packing are provided in Fig. 1. We generated ten statistical realizations for each packing density to estimate the mean and STD of the concentrations at the outlet. Thus, a total of 120 simulations were done.

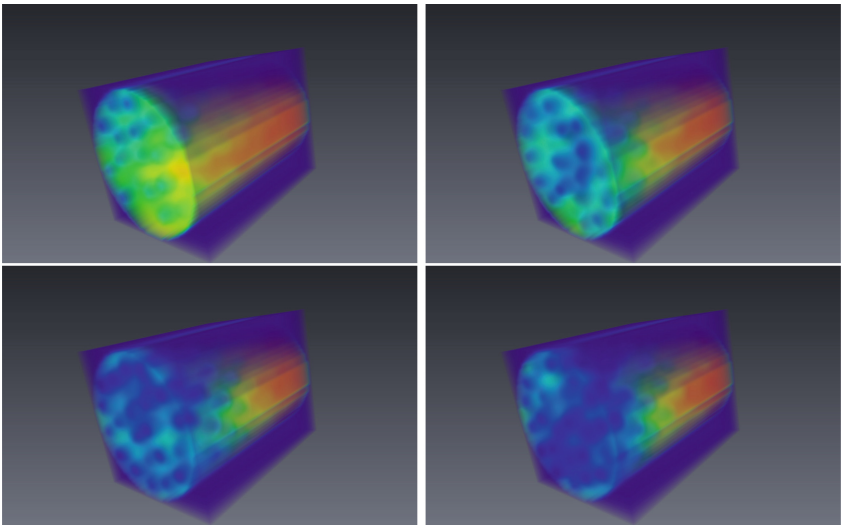


Fig. 3. The concentration of CO_2 in the computational domain at time instant $t = 7200$ s. Colorbar changes from blue ($C_{CO_2} = 0$) to red where $C_{CO_2} = 7\%$. The porosity of the left top model is 55%, porosity of the right top model is 50%, porosity of the right bottom model is 45%, and porosity of the right bottom model is 40%. (Color figure online)

First, we consider CO_2 concentration inside the reactor as presented in Fig. 3. Concentration gradually decreases from the inlet to the outlet of the reactor. It illustrates that the sorption acquires closer to the inlet, significantly preventing CO_2 penetration further to the outlet. However, as time passes, soda-lime concentration reduces near the inlet, opening the way for CO_2 flow closer to the outlet.

We also provide the 2D cross-sections of the concentration plots inside the reactor in Figs. 4, 5, 6. We considered the X_1X_2 cross-section where X_1 is the direction along the reactor, and X_2 is orthogonal to the reactor axis. We illustrate three cases corresponding to different CO_2 concentrations at the inlet, i.e., 7, 5, and 1 % of the volumetric fraction. In the cases of high values of macroporosity, the concentration field is inhomogeneous due to the existence of preferred fluid flow channels that support advective transport. On the contrary, if the macroporosity is low (45 and 40%), the reaction front is relatively homogeneous. Moreover, the propagation speed of the reaction front is approximately the same for the samples with low macroporosity. These effects are observable in Figs. 4 and 5 where the CO_2 concentration is high at the inlet. In the case of low CO_2 concentration at the inlet, the reaction front did not penetrate deep enough into the reactor because the particles close to the inlet can still do CO_2 sorption.

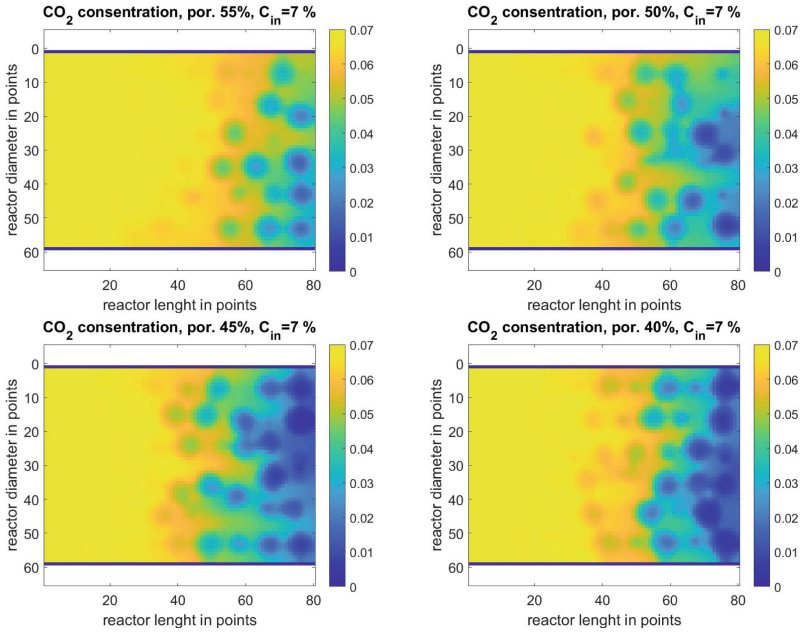


Fig. 4. The cross-section plots of CO_2 volume fraction inside the reactor at time instant $t = 7200$ s, CO_2 volume fraction at the inlet is 7%. The porosity of the left top model is 55%, porosity of the right top model is 50%, porosity of the right bottom model is 45%, and porosity of the right bottom model is 40%.

We also recorded CO_2 concentration at the outlet as a function of time. Time sampling was 7.2 s; the data was acquired at 1000 time instants. Figures 7, 8, 9 represent the break-through curves for different macroporosity values and CO_2 volume fraction at the inlet. As mentioned above, we performed simulations for ten different statistical realizations of the models with fixed macroporosity. Figures 7, 8, 9 provide the curves for all experiments. Note that in the case of high macroporosity (55 and 50%), the results for different realizations are close to each other (curves of the same color). It is due to the "homogeneity" of the flow in the macropore space. On the contrary, if the porosity is low, the fluid flow path becomes complex and may strongly depend on the pore space geometry, thus on the statistical realization of the model. Also, if the experiments with high macroporosity values are compared, one may note that the recorded

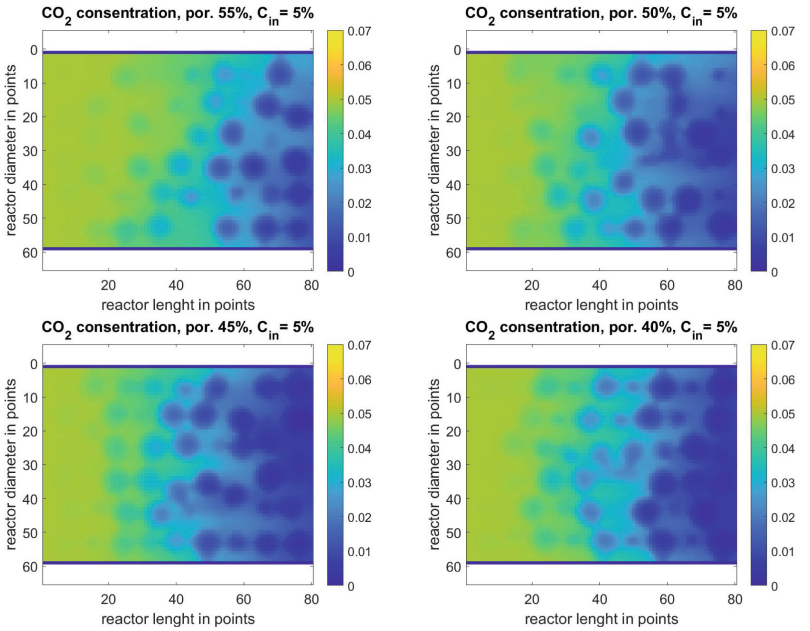


Fig. 5. The cross-section plots of CO_2 volume fraction inside the reactor at time instant $t = 7200$ s, CO_2 volume fraction at the inlet is 5%. The porosity of the left top model is 55%, porosity of the right top model is 50%, porosity of the right bottom model is 45%, and porosity of the right bottom model is 40%.

CO_2 concentration strongly depends on the macroporosity. In particular, for the experiments with 7% of CO_2 volume fraction at the inlet, the concentration at the outlet at $t = 7200$ s is about 2% for models with $\phi = 55\%$, is 1.5% for models with $\phi = 50\%$, and 1% for models with $\phi \geq 55\%$. On the contrary, we observe almost no difference in the break-through curves for the models with macroporosity greater than 55%.

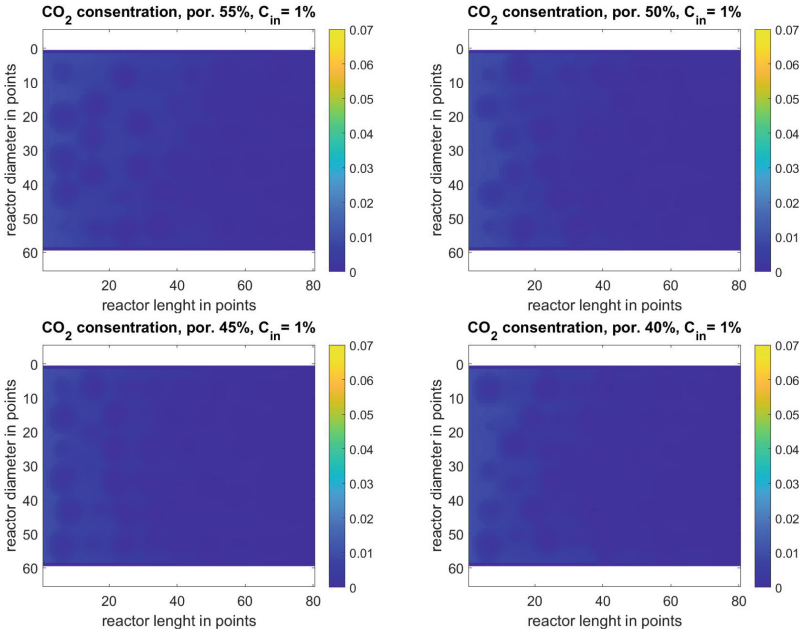


Fig. 6. The cross-section plots of CO_2 volume fraction inside the reactor at time instant $t = 7200$ s, CO_2 volume fraction at the inlet is 1%. The porosity of the left top model is 55%, porosity of the right top model is 50%, porosity of the right bottom model is 45%, and porosity of the right bottom model is 40%.

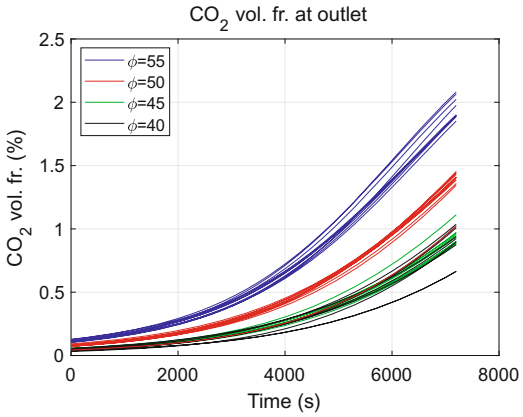


Fig. 7. The volume fraction of CO_2 at the outlet for different macroporosity inside the reactor. The volume fraction at the inlet is 7%.

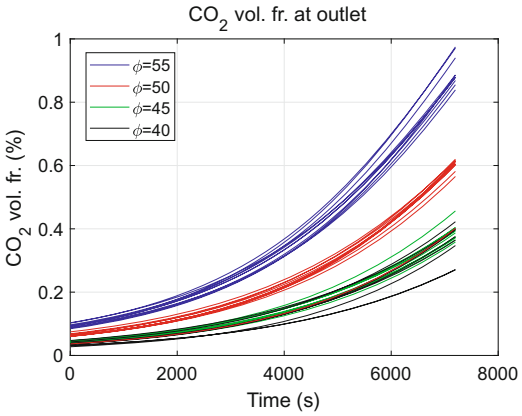


Fig. 8. The volume fraction of CO_2 at the outlet for different macroporosity inside the reactor. The volume fraction at the inlet is 5%.

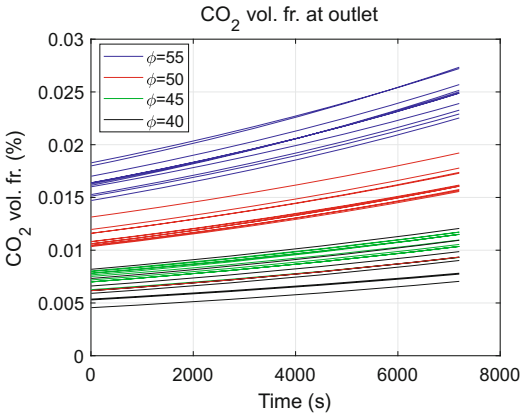


Fig. 9. The volume fraction of CO_2 at the outlet for different macroporosity inside the reactor. The volume fraction at the inlet is 1%.

6 Conclusion

In this paper, we presented the numerical algorithm to simulate the chemisorption of CO_2 by Soda-lime sorbent. The algorithm is based on a finite-difference approximation of the Stokes and advection-diffusion-reaction equation. We use the explicit finite differences for approximating the advection-diffusion term and the implicit approximation of the reaction term, solving the ADR equation with the splitting technique. The algorithm is implemented using CUDA technology; thus, it is oriented toward the use of GPUs.

We use the designed algorithm to study the effect of sorbent particle packing on the break-through time. In our experiments, we fixed the physical and chemical properties of the sorbent particles but varied the packing density

(macroporosity) and the CO_2 volume faction at the inlet. After that, the gas flow through the reactor was simulated for up to 7200 s of the model time. We measured the CO_2 volume fraction as a function of time at the outlet and fixed the volume fraction inside the reactor at the last instant.

We observed that, in the cases of high values of macroporosity, the CO_2 concentration field inside the reactor is inhomogeneous due to preferred fluid flow channels supporting advective transport. On the contrary, if the macroporosity is low (45 and 40%), the reaction front is relatively homogeneous. At the same time, if the break-through curves are considered, one may note that in the case of high macroporosity (55 and 50%), the results for different statistical realizations of the model are close to each other (curves of the same color). On the contrary, if the porosity is low, the fluid flow path becomes complex and may strongly depend on the pore space geometry, thus on the statistical realization of the model. Also, if the experiments with high macroporosity values are compared, one may note that the recorded CO_2 concentration strongly depends on the macroporosity. In particular, for the experiments with 7% of CO_2 volume fraction at the inlet, the concentration at the outlet at $t = 7200$ s is about 2% for models with $\phi = 55\%$, is 1.5% for models with $\phi = 50\%$, and 1% for models with $\phi \geq 55\%$. On the contrary, we observe almost no difference in the break-through curves for the models with macroporosity less than 45%.

References

1. Bazaikin, Y., Malkovich, E., Prokhorov, D., Derevschikov, V.: Detailed modeling of sorptive and textural properties of CaO-based sorbents with various porous structures. Sep. Purif. Technol. **255**, 117746 (2021). https://doi.org/10.1016/j.seppur.2020.117746
2. Derevschikov, V.S., Kazakova, E.D., Yatsenko, D.A., Veselovskaya, J.V.: Multiscale study of carbon dioxide chemisorption in the plug flow adsorber of the anesthesia machine. Sep. Sci. Technol. **56**(3), 485–497 (2021)
3. Derevshchikov, V.S., Kazakova, E.D.: Comparative analysis of the chemical composition and sorption, textural, and strength properties of commercial medical co2 sorbents. Catal. Ind. **12**(1), 1–6 (2020)
4. Gibou, F., Fedkiw, R., Osher, S.: A review of level-set methods and some recent applications. J. Comput. Phys. **353**, 82–109 (2018)
5. Johansen, H., Colella, P.: A cartesian grid embedded boundary method for Poisson's equation on irregular domains. J. Comput. Phys. **147**(1), 60–85 (1998)
6. Khachkova, T., Lisitsa, V., Kolyukhin, D., Reshetova, G.: Influence of interfaces roughness on elastic properties of layered media. Probab. Eng. Mech. **66**, 103170 (2021)
7. Khachkova, T., Lisitsa, V., Reshetova, G., Tcheverda, V.: GPU-based algorithm for evaluating the electrical resistivity of digital rocks. Comput. Math. Appl. **82**, 200–211 (2021)
8. Li, X., Huang, H., Meakin, P.: Level set simulation of coupled advection-diffusion and pore structure evolution due to mineral precipitation in porous media. Water Resour. Res. **44**(12), W12407 (2008)

9. Lisitsa, V., Bazaikin, Y., Khachkova, T.: Computational topology-based characterization of pore space changes due to chemical dissolution of rocks. Appl. Math. Model. **88**, 21–37 (2020). https://doi.org/10.1016/j.apm.2020.06.037
10. Lisitsa, V., Khachkova, T., Bazaikin, Y., Derevschikov, V.: Simulation of co_2 sorption from the gas stream by the grain of soda-lime sorbent. In: Gervasi, O., Murgante, B., Misra, S., Rocha, A.M.A.C., Garau, C. (eds.) Computational Science and Its Applications - ICCSA 2022 Workshops, pp. 334–347. Springer International Publishing (2022). https://doi.org/10.1007/978-3-031-10592-0_25
11. Liu, X.D., Osher, S., Chan, T.: Weighted essentially non-oscillatory schemes. J. Comput. Phys. **115**(1), 200–212 (1994)
12. Lubachevsky, B.D., Stillinger, F.H.: Geometric properties of random disk packings. J. Stat. Phys. **60**, 561–583 (1990)
13. Luo, K., Zhuang, Z., Fan, J., Haugen, N.E.L.: A ghost-cell immersed boundary method for simulations of heat transfer in compressible flows under different boundary conditions. Int. J. Heat Mass Transf. **92**, 708–717 (2016)
14. Osher, S., Fedkiw, R.P.: Level set methods: an overview and some recent results. J. Comput. Phys. **169**(2), 463–502 (2001)
15. Pollmann, N., Larsson, F., Runesson, K., Lundgren, K., Zandi, K., Jänicke, R.: Modeling and computational homogenization of chloride diffusion in three-phase meso-scale concrete. Constr. Build. Mater. **271**, 121558 (2021). https://doi.org/10.1016/j.conbuildmat.2020.121558
16. Prokhorov, D., Lisitsa, V., Khachkova, T., Bazaikin, Y., Yang, Y.: Topology-based characterization of chemically-induced pore space changes using reduction of 3d digital images. J. Comput. Sci. **58**, 101550 (2022)
17. Qiu, J.M., Shu, C.W.: Conservative high order semi-Lagrangian finite difference WENO methods for advection in incompressible flow. J. Comput. Phys. **230**(4), 863–889 (2011)

Solve the Quasi-static Biot Problem on Shared Memory Systems with Various Processors

Sergey Solovyev[1(✉)] and Vadim Lisitsa[2]

[1] Institute of Mathematics SB RAS, Koptug Avenue 4, Novosibirsk 630090, Russia
vevsa@ipgg.sbras.ru

[2] Institute of Petroleum Geology and Geophysics SB RAS, Koptug Avenue 3, Novosibirsk 630090, Russia
lisitsavv@ipgg.sbras.ru

Abstract. The quasi-static frequency domain Biot equation can be used to model loading of fluid-filled poroelastic materials in low-frequency case and to estimate effective frequency-dependent strain and stress relations. To numerically solve the Biot equation, we proposed an algorithm based on finite-difference approximation, iterative solution of the obtained system of linear algebraic equations (SLAE) and using field-split preconditioner technique. The basis of the iterative solver is the Biconjugate Gradient Stabilized (BCGStab); inverting the preconditioner is based on using the direct solver. In this paper, we present the results of implementation and testing the proposed algorithm on various shared memory systems. The experiments were performed on servers with Intel, AMD and Elbrus processors. The accuracy, memory and performance characteristics were measured. The results demonstrate robustness of the proposed algorithm on these architectures.

Keywords: Poroelasticity · Biot equation · quasi-static state · finite differences · direct methods for SLAE · iterative methods · field-split preconditioner · shared memory systems

1 Introduction

The numerical investigation of the effect of complex fracture systems on seismic waves in poroelastic fluid-saturated media is an actual problem, although studies on the theory of poroelasticity and the numerical solution of the Biot equations began in the 1950 s [4].

The object of research is the modelling of the Biot equation in the quasi-static state in the porous domain with fractures. When considering a percolating system of fractures, the size of the representative sample may exceed a hundred typical fracture sizes. It leads to grids with more than several thousand grid points

S. Solovyev— Developed the algorithm and did the numerical simulations using the supercomputer facilities of Siberian Supercomputer Center (Cluster NKS-30T) under the support of RSCF grant no. 19-77-20004-*П*. AMD and Elbrus hardware were provided by the USPARS development team.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 305–320, 2024.
https://doi.org/10.1007/978-3-031-65238-7_21

in each direction. Several numerical algorithms were presented [3,7,8]. They are based on the finite-element approximation of the quasi-static approximation of Biot equations with the mesh refinement within the fractures. However, these researhes were done for models containing only a few tens of fractures and requiring several thousand degrees of freedom for the simulation. In the study [11] we propose an algorithm for numerically upscaling of the poroelastic model for the samples containing thousands of fractures. The approach is based on the finite difference with the use of a direct solver to resolve the obtained system of linear algebraic equations with multiple righthand sides. This study of seismic attenuation was devoted to investigate the effect of fracture connectivity on WIFF and seismic attenuation. The problem of solving the system of linear algebraic equations (SLAE) is quite actual in Biot modeling. It involves computational cost problem; requires both knowledge base in mathematical algorithms for solving such systems and program implementation for high performance computing systems (HPC). The details of implementation the SLAE solution by both direct and iterative solvers with preconditioner are described in the paper [9].

The paper is structured as follows. In Sect. 2 we recall the statement of Biot equation, domain discretisation, stensils of finite-difference approximations. Section 3 is devoted to the description of the BCGStab-based iterative solver with Field-Split preconditioner. The short software implementation Sect. 4 contains information about the third-party software used. The main Sect. 5 deals with numerical experiments: three different hardware descriptions (Intel, AMD and Elbrus), visualisation of the results and characteristics of the computational process on selected architectures.

2 Poroelastic Problem in Terms of Biot Equations in Quasi-static State

In this section we describe the problem statement: differential Biot equations with boundary conditions, reconstructed effective frequency-dependent viscoelastic media, disretization and SLAE properties.

The Biot model equations stated in the quasi-static regime representing the pressure diffusion process in fluid-filled poroelastic media [2]. Table 1 presents the equations with Biot equations.

Table 1. Differential Biot equations.

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

The velocity and relative fluid velocity vectors are $\vec{u} = (u_x, u_z)^T$ and $\vec{w} = (w_x, w_z)^T$. Parameter ω is the time frequency, the fluid-saturated matrix stiffness tensor — are the coefficients $C_{11}, C_{33}, C_{13}, C_{55}$. The bone topology permeability k; the fluid-flow parametrs are M – the fluid storage coefficient, α is the Biot-Willis coefficient, η is the fluid viscousity.

Note, that the stress tensor is defined by the fourth-order stiffness tensor, the velocity vector derivatives and by αM combined with the divergence fluid velocity vector:

$$\begin{aligned}
\sigma_{xx} &= C_{11}\frac{\partial u_x}{\partial x} + C_{13}\frac{\partial u_z}{\partial z} + \alpha M\left(\frac{\partial w_x}{\partial x} + \frac{\partial w_z}{\partial z}\right) \\
\sigma_{zz} &= C_{13}\frac{\partial u_x}{\partial x} + C_{33}\frac{\partial u_z}{\partial z} + \alpha M\left(\frac{\partial w_x}{\partial x} + \frac{\partial w_z}{\partial z}\right) \\
\sigma_{xz} &= C_{55}\left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x}\right).
\end{aligned} \tag{1}$$

The components of the strain tensor are defined as:

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

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

$$\begin{aligned}
\sigma \cdot \vec{n}|_{\partial D} &= \vec{\sigma}_0 \\
\vec{w} \cdot \vec{n}|_{\partial D} &= 0.
\end{aligned} \tag{3}$$

The statement of the poroelastic problem is the recovery of the frequency dependent stiffness tensor of orthotropic viscoelastic media (Fig. 1, right). The solution of the initial problem (1) and (3) in poroelastic media (Fig. 1, left) should match the solution of the upscaled problem:

$$\frac{\partial}{\partial x}\left[\hat{C}_{11}(\omega)\frac{\partial \hat{u}_x}{\partial x} + \hat{C}_{13}(\omega)\frac{\partial \hat{u}_z}{\partial z}\right] + \frac{\partial}{\partial z}\left[\hat{C}_{55}(\omega)\left(\frac{\partial \hat{u}_x}{\partial z} + \frac{\partial \hat{u}_z}{\partial x}\right)\right] = 0, \tag{4}$$

$$\frac{\partial}{\partial x}\left[\hat{C}_{55}(\omega)\left(\frac{\partial \hat{u}_x}{\partial z} + \frac{\partial \hat{u}_z}{\partial x}\right)\right] + \frac{\partial}{\partial z}\left[\hat{C}_{13}(\omega)\frac{\partial \hat{u}_x}{\partial x} + \hat{C}_{33}(\omega)\frac{\partial \hat{u}_z}{\partial z}\right] = 0, \tag{5}$$

$$\hat{\sigma} \cdot \vec{n}|_{\partial D} = \vec{\sigma}_0 \tag{6}$$

Note, that the stress tensor of upscaled problem is defined by the fourth-order stiffness tensor and velocity vector derivatives:

$$\begin{aligned}\hat{\sigma}_{xx} &= \hat{C}_{11}\frac{\partial \hat{u}_x}{\partial x} + \hat{C}_{13}\frac{\partial \hat{u}_z}{\partial z}\\ \hat{\sigma}_{zz} &= \hat{C}_{13}\frac{\partial \hat{u}_x}{\partial x} + \hat{C}_{33}\frac{\partial \hat{u}_z}{\partial z}\\ \hat{\sigma}_{xz} &= \hat{C}_{55}(\frac{\partial \hat{u}_x}{\partial z} + \frac{\partial \hat{u}_z}{\partial x}).\end{aligned} \tag{7}$$

The strain tensor components of such problems are defined by the same formulae as for Biot (see 2).

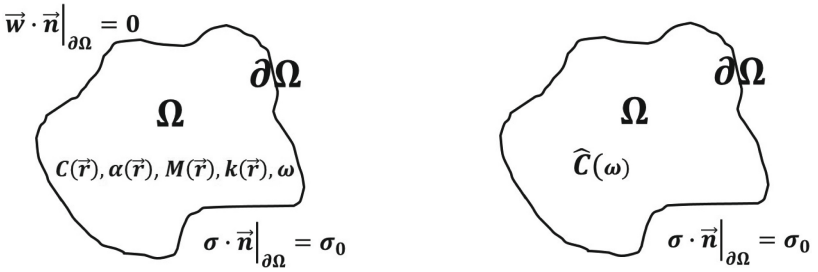


Fig. 1. Left: original fluid-saturated poroelastic media. Right: reconstructed effective frequency-dependent viscoelastic media. Vector $\vec{n}$ is the outer normal, and $C(\vec{r}), \alpha(\vec{r}), M(\vec{r}), k((\vec{r}))$ are the space-dependent parameters of Eqs. (1).

To solve the upscaling problem we need to solve the SLAE with the three right-hand sides generated by a system of equations in a square domain with three separate boundary conditions:

1. Horisontal loading: $\vec{\sigma}_{0_x x} = 1$ at left and right faces,
2. Vertical loading: $\vec{\sigma}_{0_z z} = 1$ at down and top faces,
3. Torsion loading: $\vec{\sigma}_{0_x z} = 1$ at all faces.

Details of the reconstruction algorithm are described in [12,13].

Note that apart from the solid and relative fluid velocity vectors ($\vec{u}$ and $\vec{w}$), the pressure p is useful property of the elastic problem. In poroelastic media it is:

$$-p = \alpha M\left(\frac{\partial u_x}{\partial x} + \frac{\partial u_z}{\partial z}\right) + M\left(\frac{\partial w_x}{\partial x} + \frac{\partial w_z}{\partial z}\right). \tag{8}$$

A few remarks on homogeneous media. If the coefficients η and k don't depend on spatial coordinates, then Biot equations (1) in terms of two vector unknowns ($\vec{u}$ and $\vec{w}$) lead to equations with vector $\vec{u}$ and scalar p unknowns:

$$\frac{\partial}{\partial x}\left[C_{11}\frac{\partial u_x}{\partial x} + C_{13}\frac{\partial u_z}{\partial z} - \alpha^{\mathbf{2}}\mathbf{M}(\frac{\partial \mathbf{u_x}}{\partial \mathbf{z}} + \frac{\partial \mathbf{u_z}}{\partial \mathbf{x}}) - \alpha\mathbf{p}\right] + \frac{\partial}{\partial z}\left[C_{55}(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x})\right] = 0, \tag{9}$$

$$\frac{\partial}{\partial x}\left[C_{55}\left(\frac{\partial u_x}{\partial z}+\frac{\partial u_z}{\partial x}\right)\right]+\frac{\partial}{\partial z}\left[C_{13}\frac{\partial u_x}{\partial x}+C_{33}\frac{\partial u_z}{\partial z}-\alpha\mathbf{^2M}\left(\frac{\partial \mathbf{u_x}}{\partial \mathbf{z}}+\frac{\partial \mathbf{u_z}}{\partial \mathbf{x}}\right)-\alpha\mathbf{p}\right]=0, \tag{10}$$

$$i\omega\frac{\eta}{k}\alpha\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_z}{\partial z}\right)+\left[\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial z^2}+i\omega\frac{\eta}{k}\frac{1}{M}\right]\mathbf{p}=0, \tag{11}$$

The statement (9)–(11) in comparison with (1) leads to the SLAE with smaller size. But we are interested in the general case where all poroelastic coefficients C_{11}, C_{33}, C_{13}, C_{55}, M, α, η and k depend on spatial variables.

We therefore describe the approximation of the Biot equations (1), the properties of the SLAE and ways of numerical solutions.

2.1 Discretisation of Biot Equations

Biot equations (1) have been discretised by the rectangular grid of $N_x \times N_z$ points. The domain boundaries cross the mesh cells at the centres of the cell faces as illustrated in Fig. 2. The positions of the variables on the staged grid are given in the Fig. 2. The horizontal components of the displacement vectors u_x and w_x are defined at halfinteger points in the z direction and at integer points in the x direction. Visewersa, the vertical components of the solution vector are stored at integer points in the z direction and at halfinteger points in the x direction. The coefficients of the equations are defined at the centres

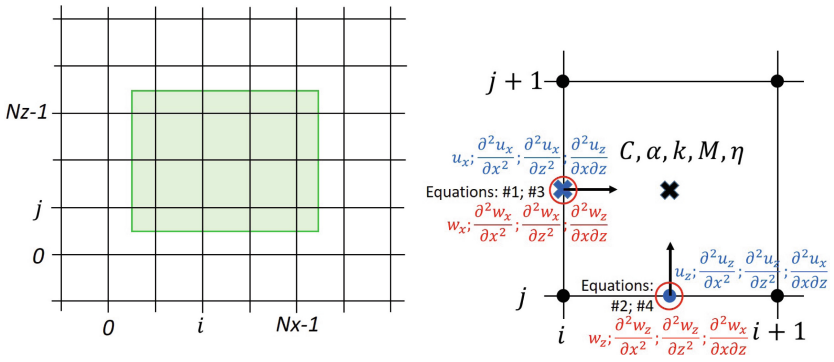


Fig. 2. Discretisation of the computational domain (left). Solution components, derivatives, location of physical parameters on the computational grid, and nodes where equations are approximated (right).

of the mesh cells (halfinteger points in both directions). The stencils used to approximate Biot's equations are shown in the Fig. (3). The details the finite difference approximation of Biot equations inside the computational domain and at its boundary (Fig. 2) are described in [10].

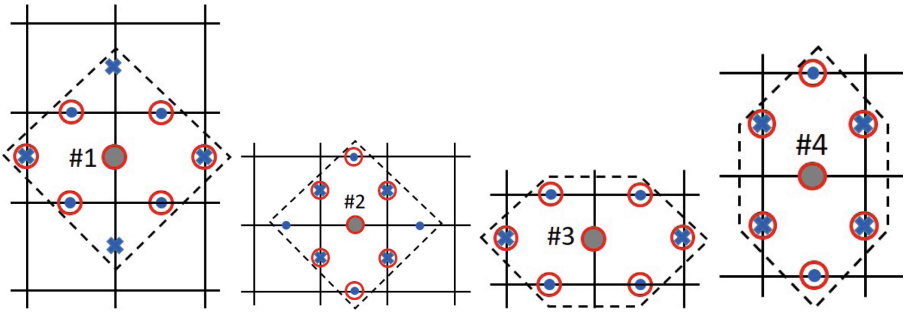


Fig. 3. Patterns of Biot equations.

Here, we need to point out the main properties of the derived system of equations. First, the matrix of the system A is a sparse square matrix, which is complex, non-Hermitian and non-symmetric. Second, due to the Neumann-type boundary conditions (3), the matrix is ill-conditioned (singular). The matrix of SLAE can be represented in "blocked form"

$$A = \begin{array}{|c|c|}\hline A_0 & A_1 \\ \hline A_2 & A_3 \\ \hline \end{array}$$

where each block corresponds to the block of Biot equations (1). The diagonal block A_0 is the symmetric semi-positive definite with the real coefficient. The diagonal block A_3 is not symmetric because of the "mixed" boundary condition (3), i.e.

$\sigma_{xx} = C_{11}\frac{\partial u_x}{\partial x} + C_{13}\frac{\partial u_z}{\partial z} + \alpha M\left(\frac{\partial w_x}{\partial x} + \frac{\partial w_z}{\partial z}\right) = \phi_x$ at the left and rigth faces;

$\sigma_{zz} = C_{13}\frac{\partial u_x}{\partial x} + C_{33}\frac{\partial u_z}{\partial z} + \alpha M\left(\frac{\partial w_x}{\partial x} + \frac{\partial w_z}{\partial z}\right) = \phi_z$ at the top and bottom faces. Such properties are derived from matrix construction and are beyond the scope of this paper. In the next section we will construct a solver based on these properties.

3 Mixed Iterative-Direct SLAE Solver

During the development of numerical solvers for SLAE, several aspects need to be considered, such as **Accuracy**, i.e. the algorithm provides a suitable solution error and residual, **Performance** – speed property, usually it involves reducing the number of floating point operations (FLOP), which should be minimised. The

details of the implementation of the developed algorithms is also an important aspect (parallelization, use of HPC third party soft, etc.). The third requirement for the solver is **Memory usage** – ability to slightly increase memory usage during the solution process. This allows for a more precise solution of the Biot problem.

There are two *Direct* and *Iterative* approaches to numerically solve SLAE. The first provides the exact solution, but requires a lot of memory to store temporary data. The second one is not so demanding on memory consumption, but the quality of solution is vary sensitive to the matrix properties. Here we use the mixed approach - develop the Iterative solver with preconditioner that uses the direct solver to inverse its submatrices. Details of implementation and compare with the direct solver is presented in the paper [9].

3.1 BCGStab Based Iterative Solver

The main idea of iterative solvers is to refine of the rough solution step by step until the specified accuracy is reached. Often this process is diverges, so the preconditioner needs to be created for the initial SLAE.

Different preconditioners [1,5,6,14] are used to speed up the convergence rate. The preconditioner B gives the SLAE: $\hat{A}x = \hat{b}$ where $\hat{A} = B^{-1}Ax$, $\hat{b} = B^{-1}b$. The BICGSTAB algorithm [15] is used to solve the complex non-hermitian matrix $\hat{A}$:

$$
\begin{aligned}
&set\ x_0 \\
&set\ j_{restart} \\
&r_0 := \hat{b} - \hat{A}x_0 \\
&p_0 := r_0 \\
&For\ j = 0, 1, \ldots, until\ convergence\ Do: \\
&a_j := \frac{(r_j, r_0^*)}{(\hat{A}p_j, r_0^*)} \\
&s_j := r_j - a_j \hat{A} p_j \\
&\omega_j := \frac{(\hat{A}s_j, s_j)}{(\hat{A}s_j, \hat{A}s_j)} \\
&x_{j+1} := x_j + \alpha_j p_j + \omega_j s_j \\
&r_{j+1} := s_j + \omega_j \hat{A} s_j \\
&If\ remainder(j/j_{restart}) = 0\ Then\ r_{j+1} := \hat{b} - \hat{A}x_{j+1} \\
&\beta_j := \frac{(r_{j+1}, r_0^*)}{(r_j, r_0^*)} \frac{\alpha_j}{\omega_j} \\
&p_{j+1} := r_{j+1} + \beta_j (p_j - \omega_j \hat{A} p_j) \\
&EndDo
\end{aligned}
\tag{12}
$$

The maximum computational complexity of the specified algorithm, i.e. the number of floating-point operations contained in the matrix $\hat{A}$ vector product (twice per step of BCGStab: $\hat{A}p_j$ and $\hat{A}s_j$). Each $\hat{A}$ vector product contains the matrix-vector product of the initial sparse matrix A (**mv**) and the inversion of the preconditioner B (**inv**). The B inversion is more expensive than the A vector product routine and is based on the use of the Field-Split preconditioning technique.

3.2 Field-Split Preconditioner

The preconditioner B should be invertible and as close as possible to the matrix of the SLAE as possible.

The reason for using Field-Split, the details of building such a preconditioner and the estimation of floating-point operations are described in the paper [9].

Here we just recall the block-low-triagonal representation of the preconditioner $B = \begin{array}{|c|c|}\hline A_0 & 0 \\ \hline A_2 & A_3 \\ \hline \end{array}$ where matrices A_0, A_2, A_3 raised from approximation the differential operators (Table 2) with boundary conditions (3).

Table 2. Differential operators of the preconditioner B.

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

The algorithm of invertion B consists of two matrix inversions A_0, A_3 and matrix A_2-vector product:

1. $x_0 = A_0^{-1} y_0$
2. $y_3 = y_3 - A_2 x_0$
3. $x_3 = A_3^{-1} y_3$

Matrix A_0 is a self-adjoint matrix with real coefficients. The A_3 has complex values on the main diagonal. The boundary conditions (3) lead to a non-symmetric of A_3.

4 Software Implementation

The Biot solver was developed in C language and used only one third party component — the direct sparse solver which is implemented in mathematical software. There are various optimized software on various architectures. The

well known highly optimised math library on Intel processors is MKL (Mathematical Kernel Library). It also shows excellent performance results on AMD architectures. The Intel MKL Pardiso component is the direct sparse solver used in Biot programme for both Intel and AMD. Special attention should be paid to the Elbrus architecture which is not supported by Intel MKL. However, like Intel MKL PARDISO, there is the USPARS direct sparse solver which has the similar functionality and is optimised for all these architectures Intel, AMD and Elbrus. Therefore, the use of USPARS was also considered in Biot programme. Some remarks on compilers: on Intel and AMD the Intel compiler was used. It takes full advantage of both Intel and AMD processors. On Elbrus system the own LCC compiler is used, specially developed for such processors. To develop and test the Biot programme, we use different servers with different modern processors, which are listed in the Table (3).

Table 3. Hardware for the numerical experiments.

	Intel(R) Xeon(R) Gold 6248R	AMD EPYC™ 7763	Elbrus 16S
web-site	ark.intel.com	www.amd.com	mcst.ru
Base Clock	3.00 GHz	2.45 GHz	2.00 GHz
1 core peak performance			
# of CPU Cores	24	64	16
RAM,G	768	1024	256

5 Numerical Experiments

There are two aspects to numerical experiments. The first is the visualisation of the physical fields resulting from the solution of the Biot equations. The second is the characteristics of the computational process on the mentioned architectures.

For the numerical experiments, we use the fracture model with interconnected cracks. The properties of the background and the cracks are given in the Table (4). The crack visualisation (material density) is shown in Fig. (4).

One of the main results is that the quality of the solution does not depend on the architecture used. Therefore, we do not clarify the architecture in the visualisation subsection.

Table 4. Properties of materials.

Coeff	Background	Crack
rho	$2.485 * 10^3$	$2.318 * 10^3$
C_{11}	$69.10 * 10^9$	$38.96 * 10^9$
C_{13}	$7.159 * 10^9$	$16.34 * 10^9$
C_{33}	$69.10 * 10^9$	$38.96 * 10^9$
C_{55}	$30.97 * 10^9$	$11.31 * 10^9$
M	$20.10 * 10^9$	$9.330 * 10^9$
αM	$5.953 * 10^9$	$6.854 * 10^9$
$\frac{\eta}{k}$	$1000 * 10^9$	$0.007 * 10^9$

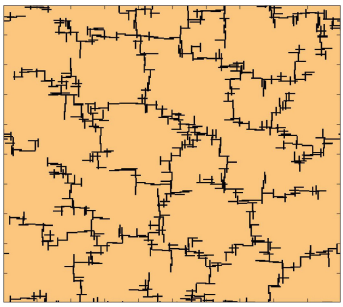


Fig. 4. Model crack.

5.1 Stress and Pressure Visualisation

The visualisation of the stress distribution for the frequency 10 Hz is shown in the Figs. (5), (6) and (7). In all of them, the lighter - the larger, the darker - the smaller value of the stress components.

The modelling results σ_{xx} and σ_{zz} of the **horizontal** loading are shown in Fig. (5) (σ_{xz} is many times smaller than the others, so it is not shown).

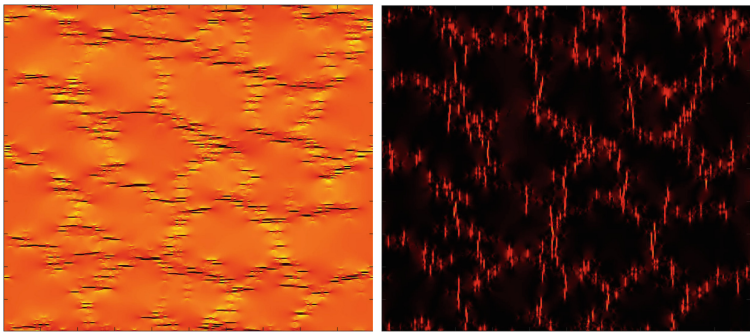


Fig. 5. Horizonal loading, stress component distribution: σ_{xx} on the left, σ_{zz} on the right.

The stress components of **vertical** loading are presented in Fig. (6) (σ_{xz} is also many times less than other, so it is not presented).

For the **torsion** loading the σ_{xz} is more than σ_{xx} and σ_{zz}. It is presented in Fig. (7).

The pressure p (see 8) is shown for different frequencies. For zero frequency, p is the same constant in the full domain for both horizontal and vertical loading. For torsional loading it is significantly less than others and is not considered. The inhomogeneous behaviour of p is observed as the frequency increases. The

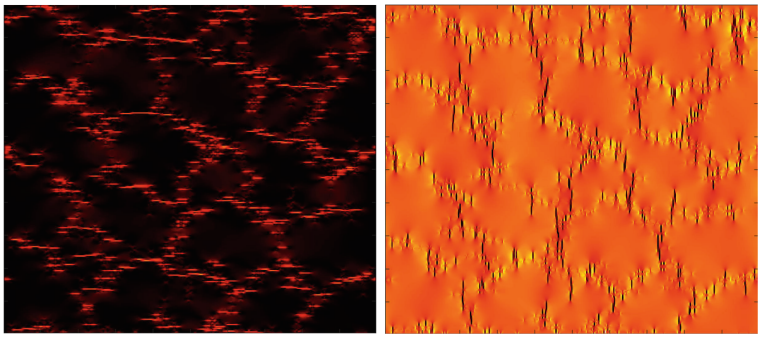


Fig. 6. Vertical loading, stress component distribution: σ_{xx} on the left, σ_{zz} on the right.

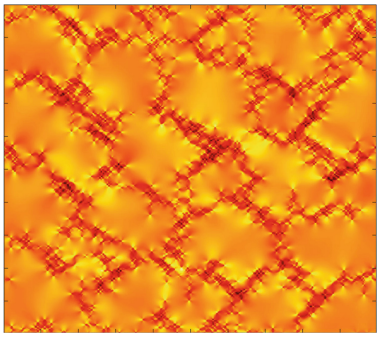


Fig. 7. Torsion loading, stress component σ_{xz} distribution.

Fig. 8 shows the p distribution for different frequencies. The average value of the pressure is the same as for the zero frequency. As the frequency increases, the pressure deviation gets closer and closer to the cracks.

5.2 Characteristics of the Computational Process

Here we are interested in two main characteristics: time and memory consumption. The implementation of Biot modelling contains main routines:

1. Read model parameters from file;
2. Approximation, i.e. construct matrix A, submatrices A_0,A_1,A_2,A_3 in CSR (Compress Sparse Row) format;
3. Solve SLAE $Ax = b$ with BCGStab including matrix-matrix multiplication and inversion preconditioner B;
4. Postprocessing: compute residual of SLAE, recover stiffness tensor.

The most expensive in terms of memory and performance is solving the SLAEs $A_0x_0 = b_0$ and $A_3x_3 = b_3$ with the inversion precondition B. As

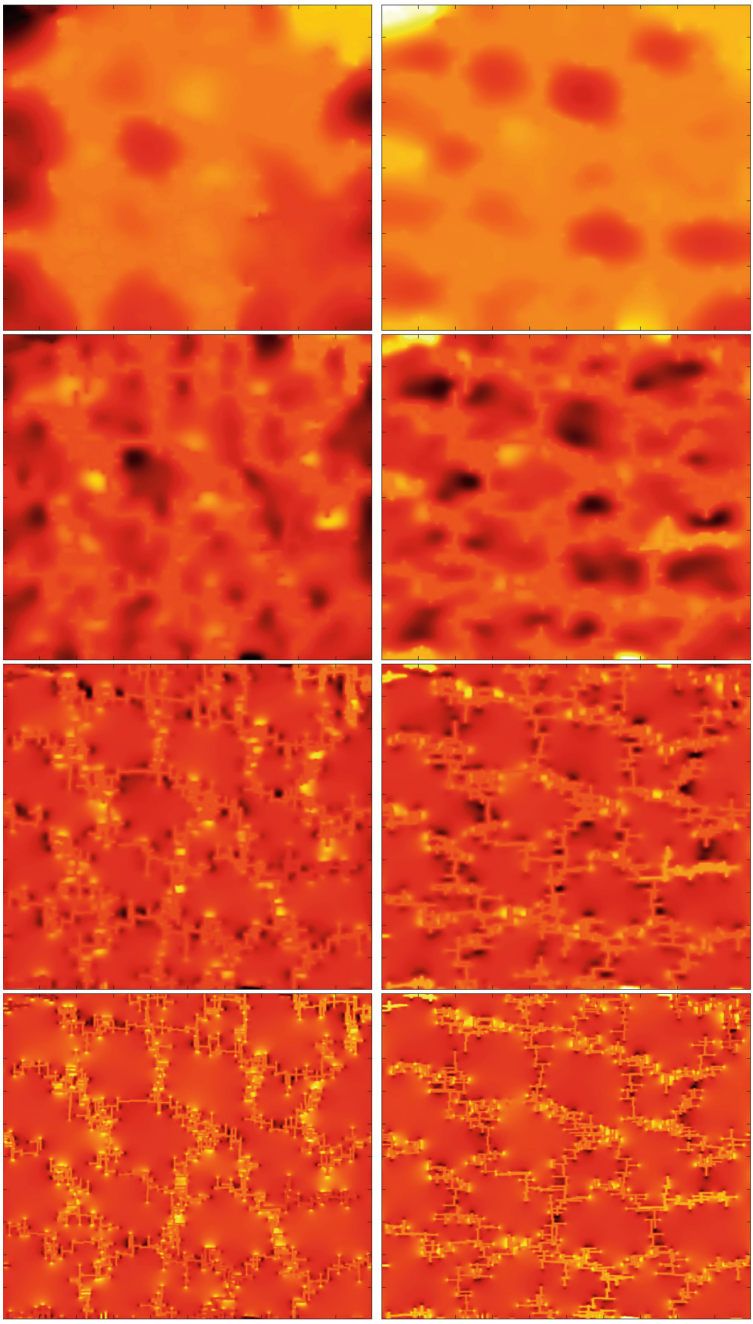


Fig. 8. Pressure for 1 Hz (top line), 10 Hz (2nd line), 100 Hz (3rd line) and 1000 Hz (bottom line); the **horizontal** load on the left, the **vertical** one on the right. The pressure for the **torsional** load is many times less than the others and is not shown.

mentioned above, this is done using highly optimised third party soft: sparse direct solvers.

First we are interested in the maximum size of the model that can be solved on systems (3). In the Table (5) we present the memory consumption of the Biot program for models of different sizes.

Table 5. Biot solver memory usage for various model sizes.

id	Mesh $n = n_x = n_z$	Problem size (# unknowns)	Peak memory usage, G
1	500	$1 * 10^6$	6
2	1000	$4 * 10^6$	25
3	2000	$16 * 10^6$	105
4	4000	$64 * 10^6$	452

The memory consumption is related to the problem size. It is predictable because the size of matrices A_0,A_1,A_2,A_3 grows linearly and the peak memory of sparse direct solvers for matrices from 2D problems has similar behaviour. This behaviour is confirmed numerically for both MKL PARDISO and USPARS solvers.

Another area of interest is timing. We measure the timing for 4 frequencies of each mesh. The Table (6) shows the total time, the percentage distribution between the treatment A_0, A_3 by the direct solver and other functions on different architectures (3). To avoid the effects of parallelization, the first results are obtained on one core of each processor.

Table 6. One core total time (sec.) for 4 frequencies, percentage of direct solvers and other functionality (**Direct/Other**).

Mesh	Intel		AMD		Elbrus
id	PARDISO	USPARS	PARDIO	USPARS	USPARS
1	116,3 (64%/36%)	122,1 (69%/31%)	79,4 (72%/28%)	85,5 (73%/27%)	261,3 (80%/20%)
2	464,1 (70%/30%)	474,3 (73%/27%)	355,4 (80%/20%)	354,0 (80%/20%)	1043,1 (82%/18%)
3	2 323,0 (78%/22%)	2 219,5 (77%/23%)	2 191,7 (87%/13%)	1 877,5 (85%/15%)	4986,0 (86%/14%)
4	15 156,6 (80%/20%)	11 431,9 (81%/19%)	14 925,0 (89%/11%)	11 670,8 (88%/12%)	N/A

Although the direct solvers are very expensive, the table shows that they are compatible with other routines. This can be explained by their high degree of optimisation. On the other hand, the proportion of direct solvers increases with the size of the problem.

The next Table (7) shows the multi-core potential of Biot solvers. The processors have different numbers of cores, so we measure the scalability on the same number of cores — 16.

Table 7. Many core (16) total time (sec.) for 4 frequencies, percentage of direct solvers and other functionality (**Direct/Other**).

Mesh	Intel		AMD		Elbrus
id	PARDISO	USPARS	PARDIO	USPARS	USPARS
1	71,8 (58%/42%)	74,3 (60%/40%)	42,9 (53%/47%)	50,8 (59%/41%)	184,4 (72%/28%)
2	249,8 (60%/40%)	252,1 (61%/39%)	144,4 (59%/41%)	173,2 (64%/36%)	686,0 (73%/27%)
3	1 066,1 (65%/35%)	1 037,7 (65%/35%)	647,7 (66%/34%)	712,2 (67%/33%)	2 805,0 (74%/26%)
4	6 422,8 (65%/35%)	4 546,6 (65%/35%)	3 676,2 (66%/34%)	3 515,7 (67%/33%)	N/A

Computing time for 16 cores is less than for one, but scalability is poor. The time contribution of the direct solvers has become smaller due to their good parallelization. The poor scalability of other functionalities can be explained by

Table 8. Maximum core total time (sec.) for 4 frequencies, percentage of direct solvers and other functionality (**Direct/Other**).

Mesh	Intel		AMD		Elbrus
Mesh	24 cores		64 cores		16 cores
id	PARDISO	USPARS	PARDIO	USPARS	USPARS
1	69,0 (58%/42%)	72,1 (60%/40%)	43,7 (52%/48%)	50,9 (59%/41%)	see Table 7
2	247,7 (60%/40%)	255,8 (61%/39%)	140,3 (57%/43%)	168,3 (63%/37%)	see Table 7
3	1 063,1 (61%/39%)	1 034,3 (62%/38%)	580,8 (60%/40%)	671,3 (65%/35%)	see Table 7
4	5 110,3 (66%/34%)	5 514,4 (62%/38%)	3 305,7 (62%/38%)	3 172,1 (64%/36%)	see Table 7

the existence of a large number of different functionalities, which makes their parallelization very difficult. On the other hand, it is the Biot solver that has the potential for improvement.

The third measurement was made on the maximum number of cores for each processor. The Table (8) shows that there is no significant reduction in computing time. This is due to poor scalability. However, the absolute times for all processors and for each of the direct solvers (PARDISO and USPARS) are reasonable.

6 Conclusion

We presented results of the implementation of the algorithm for solving the discretised Biot equation in quasi-static state based on the BCGStab iterative solver with field-split preconditioner. The aim of the research was to investigate the behaviour of the algorithm on different architectures such as Intel, AMD and Elbrus. In addition to our own implementation of the main functionality, the third party libraries were used to solve SLAE with preconditioner blocks. Similar results with good solution quality were obtained on different architectures. The characteristics of the computational process such as number of iterations, memory consumption were also similar. Although the solution time varies on different hardware, it does not increase dramatically with model size. The scalability is far from ideal and the algorithm has potential for improvement. However, this is not critical as the largest Biot problem can be solved in a reasonable time. The main conclusion is that the proposed Biot solver can be successfully used for poroelasticity modelling on hardware systems with different processors.

References

1. Belonosov, M., Kostin, V., Neklyudov, D., Tcheverda, V.: 3d numerical simulation of elastic waves with a frequency-domain iterative solver. Geophysics **83**(6), T333–T344 (2018)
2. Biot, M.A.: Theory of propagation of elastic waves in fluid-saturated porous solid. i. low-frequency range. J. Acoustical Soc. America **28**, 168–178 (1956)
3. Carcione, J.M., Santos, J.E., Picotti, S.: Anisotropic poroelasticity and wave-induced fluid flow: harmonic finite-element simulations. Geophys. J. Int. **186**(3), 1245–1254 (2011)
4. Carcione, J.M., Morency, C., Santos, J.E.: Computational poroelasticity – a review. Geophysics **75**(5), 75A229-75A243 (2010)
5. Evstigneev, N.M., Ryabkov, O.I., Gerke, K.M.: Stationary stokes solver for single-phase flow in porous media: a blastingly fast solution based on algebraic multigrid method using gpu. Adv. Water Resour. **171**, 104340 (2023)
6. Khachkova, T., Lisitsa, V., Reshetova, G., Tcheverda, V.: Gpu-based algorithm for evaluating the electrical resistivity of digital rocks. Comput. Math. Appl. **82**, 200–211 (2021)
7. Quintal, B., Steeb, H., Frehner, M., Schmalholz, S.M.: Quasi-static finite-element modeling of seismic attenuation and dispersion due to wave-induced fluid flow in poroelastic media. J. Geophys. Res. **116**, B01201 (2011)

8. Rubino, J.G., Caspari, E., Müller, T.M., Milani, M., Barbosa, N.D., Holliger, K.: Numerical upscaling in 2-d heterogeneous poroelastic rocks: anisotropic attenuation and dispersion of seismic waves. J. Geophys. Res. Solid Earth **121**(9), 6698–6721 (2016)
9. Solovyev, S., Lisitsa, V.: Field-split iterative solver vs direct one forquasi-static biot equation. In: Voevodin, V., Sobolev, S., Yakobovskiy, M., Shagaliev, R. (eds.) Supercomputing, pp. 86–99. Springer Nature Switzerland, Cham (2023). https://doi.org/10.1007/978-3-031-49432-1_7
10. Solovyev, S., Novikov, M., Lisitsa, V.: Numerical solution of anisotropic biot equations in quasi-static state. In: Gervasi, O., Murgante, B., Misra, S., Rocha, A.M.A.C., Garau, C. (eds.) Computational Science and Its Applications - ICCSA 2022 Workshops, pp. 310–327. Springer International Publishing (2022). https://doi.org/10.1007/978-3-031-10562-3_23
11. Solovyev, S., Novikov, M., Lisitsa, V.: A numerical investigation of wave-induced fluid flows in anisotropic fractured porous media. Comput. Math. Appli. **140**, 78–88 (2023). https://doi.org/10.1016/j.camwa.2023.03.013, https://www.sciencedirect.com/science/article/pii/S0898122123001098
12. Solovyev, S., Novikov, M., Lisitsa, V.V.: Numerical solution of anisotropic biot equations in quasi-static state. In: Computational Science and Its Applications - ICCSA 2022 Workshops - Malaga, Spain, July 4-7, 2022, Proceedings, Part II, pp. 310–327 (2022). https://doi.org/10.1007/978-3-031-10562-3_23
13. Solovyev, S., Novikov, M., Lisitsa, V.: Numerical solution of anisotropic biot equations of poroelastic fluid-saturated media in quasi-static state for numerical upscaling. Numerical Methods Program.(Vychislitelnye Metody i Programmirovanie) **24**(75), 67–88 (2023). https://doi.org/10.26089/NumMet.v24r106, https://en.num-meth.ru/index.php/journal/article/view/1257
14. Stuben, K.: A review of algebraic multigrid. J. Comput. Appl. Math. **128**(1–2), 281–309 (2001)
15. Saad, Y.: Iterative Methods for Sparse Linear Systems. PWS Publishing, New York (1996)

Computational Analysis of Seismic Waves Attenuation Caused by Porosity Variability in a Fluid-Saturated Porous Model of Thawing Permafrost

Galina Reshetova[1(✉)], Mikhail Novikov[2], and Evgeniy Romenski[3]

[1] Institute of Computational Mathematics and Mathematical Geophysics SB RAS, Novosibirsk 630090, Russia
kgv@nmsf.sscc.ru

[2] Trofimuk Institute of Petroleum Geology and Geophysics SB RAS, Novosibirsk 630090, Russia
novikovma@ipgg.sbras.ru

[3] Sobolev Institute of Mathematics SB RAS, Novosibirsk 630090, Russia
evrom@math.nsc.ru

Abstract. A computational model for wave fields simulation in a saturated deformable porous medium is presented. The governing differential equations of the model are derived from a general Symmetric Hyperbolic Thermodynamically Compatible (SHTC) two-phase model of saturated porous medium and form a linear PDE system allowing the application of an efficient finite difference method on a staggered grid. A series of numerical test problems showed a strong dependence of wave attenuation on porosity and relaxation time coefficient. It was also shown that the constitutive equations of the SHTC give a constant value of the quality factor over a range of seismic frequencies, making it possible to use the SHTC model to develop seismic methods for monitoring permafrost thaw.

Keywords: Wave field simulation · Fluid saturated porous medium · Quality factor · Staggered grid finite difference scheme

1 Introduction

In recent years, there has been growing interest in the development of methods for seismic monitoring of permafrost thawing, caused, in particular, by global warming. These studies are undoubtedly important since soil thawing leads to a loss of its bearing capacity and, as a result, can lead to catastrophic consequences, such as the destruction of buildings and communications. Therefore, a particularly important task is the development of seismic monitoring methods that make it possible to characterize changes in the physical properties of

This work was financially supported by the Russian Science Foundation, grant No. 22-11-00104.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 321–333, 2024.
https://doi.org/10.1007/978-3-031-65238-7_22

permafrost depending on changes in wave fields with changes in ambient temperature [1–3].

Seismic monitoring is based on the analysis of wave fields, their propagation and reflection in the upper layers of the Earth's crust, including areas of permafrost, which from the point of view of continuum mechanics is a complex geological deformable medium. The variability of wave fields in response to external conditions can be used to assess changes in permafrost zones and predict critical events. As temperatures rise in permafrost zones, ice melts, forming a porous structure that can contain water and gases as a result of melting. To describe the complex structure of the permafrost zone under the influence of temperature, a mathematical model of a deformable porous medium saturated with a multiphase mixture of liquids and gases is required.

For the modelling of seismic waves, the most common approach was proposed by Biot in the middle of the last century and further developed in applications to geophysics [4–6]. Biot's theory is a linear theory of a medium consisting of an elastic porous skeleton and a fluid filling the pores, the equations of which are derived under certain assumptions based on the definitions of the elastic deformation energy density function and the kinetic energy. It predicts three types of waves: fast and slow compressional waves and shear waves, and can be successfully used to study various seismic problems. However, its application to wave modelling for porosities close to 0 and 1 is problematic, and it is also unclear how to generalise the Biot model to the case of finite deformations.

We use an alternative model of small amplitude wave propagation in a saturated porous medium, obtained by simplifying the general symmetric hyperbolic thermodynamically compatible (SHTC) porous medium model [7,8]. The theory of SHTC equations allows to design new mathematically and physically correct models of complex media [9–11]. The governing equations of the SHTC poroelasticity model, in contrast to widely used models of wave processes such as the Biot model [4–6], are applicable in a wide range of porosity variations, including its limits of 0 and 1. The analysis of wave propagation using the SHTC model gives results close to those known from Biot's theory [7]. In addition, the SHTC model provides a direct way of modelling waves in the case where the saturating fluid is a multiphase mixture of liquids and gases [12,13].

In our studies, we assume that thawing permafrost can be interpreted as a poroelastic medium with changing porosity during the transition from solid to liquid phase. This means that, depending on the temperature and pressure within the thawing permafrost, it can either be frozen (solid state) or gradually change to a liquid state (water) as the temperature rises.

Field and laboratory data indicate that there is a relationship between the degree of permafrost thaw and the degree of seismic wave attenuation in such media. We therefore suggest that the main criterion for the degree of permafrost thaw may be an estimate of the degree of seismic wave attenuation in such a medium.

In order to correctly model seismic wave fields in a complex geological environment, transitioning from an elastic medium (ice) to a poroelastic medium

(melting permafrost), and then to a liquid medium (water), it is necessary to be able to qualitatively describe the properties of the seismic wave fields in the model. In particular, it is necessary to know how attenuation mechanisms are taken into account in the SHTC model and whether constant quality factor is ensured throughout the seismic frequency range.

2 SHTC System for Wave Field Simulation in Deformed Saturated Porous Medium

2.1 Governing Equations

This section presents a linear system of first-order partial differential equations for small-amplitude wave propagation, derived from the general SHTC system of governing equations for a saturated deformable porous medium [7,8]. Let us consider a stationary, unstressed porous medium, saturated with fluid, in which the density of the skeleton is ρ_2, and the density of the saturating liquid is ρ_1. Assume that a saturated porous medium is a two-phase solid-fluid mixture with the volume fractions of fluid α_1 and solid $\alpha_2 = 1 - \alpha_1$. The porosity coincides with the volume fraction of the saturating liquid $\phi = \alpha_1$. The following state variables are used for simulation of wave propagation: v_i - the velocity of the mixture, w_i - the relative velocity of the fluid motion relative to the skeleton, p - the pressure of the mixture (the same for both phases), σ_{ij} - the stress deviator in the mixture.

$$\begin{aligned}
&\rho\frac{\partial v_i}{\partial t} + \frac{\partial p}{\partial x_i} - \frac{\partial \sigma_{ik}}{\partial x_k} = F_i,\\
&\frac{\partial w_k}{\partial t} + \left(\frac{1}{\rho_1} - \frac{1}{\rho_2}\right)\frac{\partial p}{\partial x_k} = -\chi w^k,\\
&\frac{\partial p}{\partial t} + K\frac{\partial v_k}{\partial x_k} + \frac{\alpha_1\alpha_2}{\rho}\left(\rho_2 - \rho_1\right)K\frac{\partial w_k}{\partial x_k} = 0,\\
&\frac{\partial \sigma_{ik}}{\partial t} - \mu\left(\frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i} - \frac{2}{3}\delta_{ik}\frac{\partial v_j}{\partial x_j}\right) = -\frac{\sigma_{ik}}{\tau}.
\end{aligned} \tag{1}$$

The mixture and relative velocities are connected with solid and fluid phase velocities v_2^i and v_1^i as $v_i = c_1 v_1^i + c_2 v_2^i$ and $w_i = v_1^i - v_2^i$ respectively, where $c_1 = \alpha_1\rho_1/\rho$, $c_2 = \alpha_2\rho_2/\rho$ are phase mass fractions and $\rho = \alpha_1\rho_1 + \alpha_2\rho_2$ is the mixture density. The bulk modulus of the mixture K is related to the bulk moduli of the constituents K_1, K_2 by the relation $K = (\alpha_1/K_1 + \alpha_2/K_2)^{-1}$. $\mu = \alpha_2\mu_2$ is the shear modulus of the mixture, μ_2 is the shear modulus of the material of skeleton. F_i defines the external force source exciting the wave field. Right hand side of the equation for the relative velocity w_k contains interphase friction force with the friction coefficient $\chi = c_1c_2/\theta$. In the right hand side of equation for the stress deviator σ_{ik} there is shear stress relaxation term with relaxation time τ.

Our goal is to study the influence of temperature changes on the properties of wave fields based on solving system (1). It is clear that the coefficients in

the equations (material constants) change depending on the temperature. But in the range of its change that interests us, near the melting temperature of ice, the material parameters of the solid and liquid phases change insignificantly, except for the change in porosity. Porosity can rise from 0 significantly as ice melts. Therefore, in what follows we neglect the change in densities and moduli of phases depending on temperature and study the dependence of wave fields only on temperature changes in porosity.

Thus, the list of parameters in (1) which can be a function of porosity $\alpha_1 = \phi$ generated by the temperature variation:

- $\rho = \phi\rho_1 + (1-\phi)\rho_2$ - the total density of the mixture
- $c_1 = \phi\rho_1/\rho_0, c_2 = 1 - c_1 = (1-\phi)\rho_2/\rho$ - phase mass fractions
- $K = (\phi K_1^{-1} + (1-\phi)K_2^{-1})^{-1}$ - the bulk modulus of the mixture
- $\mu = (1-\phi)\mu_2$ - the shear modulus of the mixture
- θ - the relative velocity relaxation time, $\theta^{-1} \sim \eta/k$ (η - viscosity k - permeability)
- τ - shear stress relaxation time

Of course θ and τ depend on porosity. Since we have no available data on this dependence, in this paper we assume that there is no friction $\theta = \infty$ and study the qualitative wave fields behaviour varying τ for different values of porosity.

2.2 Energy Dissipation

The important property of the system (1) is the energy dissipation produced by the source terms. The energy balance equation can be obtained by transforming system (1) to a symmetric form and then deriving the energy integral by multiplying all equations by the appropriate coefficients and summing them up. Below we simply present a final result. The total energy of the medium should be defined as

$$\mathcal{E} = \rho\frac{v_n v_n}{2} + \rho c_1 c_2 \frac{w_n w_n}{2} + \frac{1}{2K}p^2 + \frac{\sigma_{ij}\sigma_{ij}}{2\mu}.$$

Thus, in order to obtain the law of energy balance, it is necessary to multiply the equations of system (1), respectively, by v_i, $\rho c_1 c_2 w_k$, p/K, $\sigma_{ik}/(2\mu)$. Summing everything up, we arrive at the equation

$$\frac{\partial \mathcal{E}}{\partial t} + \frac{\partial\left(pv_k + \rho c_1 c_2\left(\frac{1}{\rho_1} - \frac{1}{\rho_2}\right)pw_k - \sigma_{ik}v_i\right)}{\partial x_k} = -\frac{\rho(c_1c_2)^2 w_n w_n}{2\theta} - \frac{\sigma_{ij}\sigma_{ij}}{2\mu\tau}. \quad (2)$$

In the right hand side of the energy balance Eq. (2) there is a negative source term appeared due to the interphase friction and shear stress relaxation. This source term produces the energy dissipation which causes waves attenuation.

It is important to emphasise that the process of seismic wave attenuation in porous media is a complex phenomenon influenced by various factors such as the structure of the medium, the properties of the fluid and the elastic skeleton, the wave characteristics of the seismic wave and others.

In particular, the main factors leading to the attenuation of seismic energy in the poroelastic medium are internal interfacial friction and stress relaxation. Interfacial friction in porous media refers to the frictional force between different phases in the medium, e.g. between a liquid and a solid phase. Stress relaxation processes are processes in which stresses decrease after the application of an external force. For example, in the context of melting ice, stress relaxation occurs when the ice changes from a solid to a liquid state, resulting in a reduction of stresses in the material. This process is influenced by temperature change and the solid-liquid transition, which together favour stress relaxation in porous media.

Various mathematical models are used to describe the attenuation of seismic energy in the medium, in particular the widely used Generalised Standard Linear Solid (GSLS) model [14], which takes into account both elastic and viscous properties of the medium.

The quality factor (Q-factor) is used to estimate the energy absorption of seismic waves propagating through a medium and is defined as $Q = 2\pi(E/\delta E)$, where $(E/\delta E)$ is the fraction of energy loss per cycle. The assumption of constancy of the seismic Q-factor is fundamental to seismic research. This assumption implies that the Q-factor remains constant over the entire seismic frequency spectrum. The GSLS model is based on the assumption of near constancy of Q, which makes it a proven tool for the study of wave fields in attenuated media.

In order to be confident that our proposed model also provides a constant Q-factor over the seismic frequency range, it is necessary to perform numerical tests.

3 Finite Difference Method

Our numerical approach is based on the staggered grid finite difference method [15,16]. In the context of two dimensions, we introduce new symbols for the coordinates $x = x_1$, $y = x_2$ and the state variables $V_x = V_1$, $V_y = V_2$, $W_x = W_1$, $W_y = W_2$, $\Sigma_{xx} = \Sigma_{11}$, $\Sigma_{yy} = \Sigma_{22}$, $\Sigma_{xy} = \Sigma_{12}$.

Within the (t, x, y) space-time framework, we construct a grid with integer nodes at $t^n = n\Delta t$, $x_i = i\Delta x$, $y_j = j\Delta y$, and semi-integer nodes at $t^{n+1/2} = (n + 1/2)\Delta t$, $x_{i+1/2} = (i + 1/2)\Delta x$, $y_{j+1/2} = (j + 1/2)\Delta y$, where Δt, Δx and Δy represent the grid spacings in time and space.

The staggered grid finite difference method is based on the finite volume discretization method presented in particular in [17], and is often applied to systems of equations derived from physical conservation laws. A key advantage of this approach is that it eliminates the need to approximate fluxes during the solution, as the flux values are known, increasing the efficiency and reliability of the method. As part of this technique, we define the stresses and velocities at different grid points in space and time to provide a second-order accuracy approximation with a minimal difference scheme template.

It is assumed that the material parameters remain constant within each grid cell $[x_{i-1/2}, x_{i+1/2}] \times [y_{j-1/2}, y_{j+1/2}]$, allowing for potential discontinuities along the grid boundaries.

The mixture velocities V_x, V_y and the relative velocities W_x, W_y are defined at specific points $(i+1/2, j)$, $(i, j+1/2)$ and denoted as $(V_x)^n_{i+1/2,j}$, $(V_y)^n_{i,j+1/2}$, $(W_x)^n_{i+1/2,j}$, $(W_y)^n_{i,j+1/2}$.

Pressure and deviatoric stresses are assigned to points (i, j) as $(P)^{n+1/2}_{i,j}$, $(\Sigma_{xx})^{n+1/2}_{i,j}$, $(\Sigma_{yy})^{n+1/2}_{i,j}$, and the shear stress is assigned to the points $(i+1/2, j+1/2)$ as $(\Sigma_{xy})^{n+1/2}_{i+1/2,j+1/2}$. The spatial arrangement of the nodes on the staggered grid is shown in Fig. 1.

For compactness, let us introduce a few notations for a discrete function $f^n_{i,j} = f(t^n, x_i, y_j)$:

– Second-order central difference operators

$$D_t[f]^n_{i,j} = \frac{(f)^{n+1/2}_{i,j} - (f)^{n-1/2}_{i,j}}{\Delta t}, \qquad A_t[f]^n_{i,j} = \frac{(f)^{n+1/2}_{i,j} + (f)^{n-1/2}_{i,j}}{2}, \tag{3}$$

– Fourth-order central difference operators (Levander stencil)

$$D_x[f]^n_{i,j} = \frac{1}{\Delta x}\left\{\frac{9}{8}\left((f)^n_{i+1/2,j} - (f)^n_{i-1/2,j}\right) - \frac{1}{24}\left((f)^n_{i+3/2,j} - (f)^n_{i-3/2,j}\right)\right\}, \tag{4}$$

$$D_y[f]^n_{i,j} = \frac{1}{\Delta y}\left\{\frac{9}{8}\left((f)^n_{i,j+1/2} - (f)^n_{i,j-1/2}\right) - \frac{1}{24}\left((f)^n_{i,j+3/2} - (f)^n_{i,j-3/2}\right)\right\}, \tag{5}$$

– Volumetric arithmetic averaging

$$\langle f\rangle_{i+1/2,j} = (f_{i,j} + f_{i+1,j})/2, \qquad \langle f\rangle_{i,j+1/2} = (f_{i,j} + f_{i,j+1})/2, \tag{6}$$

– Harmonic averaging by [18]

$$\{f\}_{i+1/2,j+1/2} = \left[\frac{1}{4}\left(\frac{1}{f_{i,j}} + \frac{1}{f_{i+1,j}} + \frac{1}{f_{i,j+1}} + \frac{1}{f_{i+1,j+1}}\right)\right]^{-1}. \tag{7}$$

Using these notations, the finite difference equations can be written as

$$\begin{aligned} D_t[V_x]^{n-1/2}_{i+1/2,j} = &-\left\langle 1/\rho^0\right\rangle_{i+1/2,j} D_x[P]^{n-1/2}_{i+1/2,j} \\ &+\left\langle 1/\rho^0\right\rangle_{i+1/2,j}\left(D_x[\Sigma_{xx}]^{n-1/2}_{i+1/2,j} + D_y[\Sigma_{xy}]^{n-1/2}_{i+1/2,j}\right) + [F_x]^{n-1/2}_{i+1/2,j}, \end{aligned} \tag{8}$$

$$\begin{aligned} D_t[V_y]^{n-1/2}_{i,j+1/2} = &-\left\langle 1/\rho^0\right\rangle_{i,j+1/2} D_y[P]^{n-1/2}_{i,j+1/2} \\ &+\left\langle 1/\rho^0\right\rangle_{i,j+1/2}\left(D_x[\Sigma_{xy}]^{n-1/2}_{i,j+1/2} + D_y[\Sigma_{yy}]^{n-1/2}_{i,j+1/2}\right) + [F_y]^{n-1/2}_{i,j+1/2}, \end{aligned} \tag{9}$$

$$\begin{aligned} D_t[W_x]^{n-1/2}_{i+1/2,j} = &-\left\langle 1/\rho^0_1 - 1/\rho^0_2\right\rangle_{i+1/2,j} D_x[P]^{n-1/2}_{i+1/2,j} \\ &-\left\langle c^0_1 c^0_2/\theta_2\right\rangle_{i+1/2,j} A_t[W_x]^{n-1/2}_{i+1/2,j}, \end{aligned} \tag{10}$$

$$D_t[W_y]^{n-1/2}_{i,j+1/2} = -\left\langle 1/\rho_1^0 - 1/\rho_2^0 \right\rangle_{i,j+1/2} D_y[P]^{n-1/2}_{i,j+1/2} - \left\langle c_1^0 c_2^0/\theta_2 \right\rangle_{i,j+1/2} A_t[W_y]^{n-1/2}_{i,j+1/2}, \tag{11}$$

$$D_t[P]^n_{i,j} = -(K)_{i,j}\left(D_x[V_x]^n_{i,j} + D_y[V_y]^n_{i,j}\right) - \left((\rho_2^0 - \rho_1^0)\alpha_1^0\alpha_2^0 K/\rho^0\right)_{i,j}\left(D_x[W_x]^n_{i,j} + D_y[W_y]^n_{i,j}\right), \tag{12}$$

$$D_t[\Sigma_{xx}]^n_{i,j} = (\mu)_{i,j}\left(\frac{4}{3}D_x[V_x]^n_{i,j} - \frac{2}{3}D_y[V_y]^n_{i,j}\right) - (1/\tau)_{i,j}A_t[\Sigma_{xx}]^n_{i,j}, \tag{13}$$

$$D_t[\Sigma_{yy}]^n_{i,j} = (\mu)_{i,j}\left(\frac{4}{3}D_y[V_y]^n_{i,j} - \frac{2}{3}D_x[V_x]^n_{i,j}\right) - (1/\tau)_{i,j}A_t[\Sigma_{yy}]^n_{i,j}, \tag{14}$$

$$D_t[\Sigma_{xy}]^n_{i+1/2,j+1/2} = \{\mu\}_{i+1/2,j+1/2}\left(D_x[\Sigma_y]^n_{i+1/2,j+1/2} + D_y[V_x]^n_{i+1/2,j+1/2}\right) - \{1/\tau\}_{i+1/2,j+1/2}A_t[\Sigma_{xy}]^n_{i+1/2,j+1/2}. \tag{15}$$

The scheme obtained is an explicit finite difference scheme of second order accuracy in time and space for a homogeneous elastic medium. Stability conditions and dispersion properties can be found in [15].

4 Numerical Test Problem

As mentioned above, the correct behaviour of the seismic wave fields described by system (1) should ensure a constant Q-factor over the range of seismic frequencies.

The wave attenuation mechanisms included in system (1) are taken into account by introducing two right-hand terms into the equations for the relative velocities w_i and for the stress deviator σ_{ik}.

The first term corresponds to the interfacial frictional force with the friction coefficient $\chi = c_1 c_2/\theta$. The second term corresponds to the shear stress relaxation with relaxation time τ.

Preliminary calculations have shown that interphase friction mainly attenuates the slow P-wave (Biot wave), while the term responsible for shear stress relaxation affects the attenuation of the fast P- and S-waves. In the seismic frequency range, the slow P-wave attenuates rapidly and its amplitude becomes negligible, so this wave may not be taken into account when interpreting seismic data. For this reason, we focus on the mechanism of shear stress relaxation and its effect on wave attenuation, assuming $\chi = 0$ in further calculations.

Consider a homogeneous poroelastic medium with the material parameters given in Table 1. We assume that the thawing permafrost can be considered as a poroelastic medium with varying porosity. Depending on the temperature and pressure within the thawing permafrost, it may be either frozen (solid state) or in the process of transitioning to a liquid state (water) as the temperature rises.

In the frozen state, i.e. ice, it can be considered as a limiting case of poroelastic medium by setting the porosity (equal to the volume fraction of liquid $\phi = \alpha_1^0$) to 0 in system (1). During the melting process, the porosity of the medium increases to the value of the pure liquid state $\phi = 1$.

The calculations were carried out for the domain (800×800) m. The wave field is excited by a vertical type source with $F_x(x, y, t) = 0$ and $F_y(x, y, t) = \delta(x_0, y_0) f(t)$, where δ is the Dirac delta function that locates the source in the centre of the domain $(x_0, y_0) = (400, 400)$ m. The time function $f(t)$ is given by the Ricker wavelet $f(t) = (1 - \omega^2 (t - t_0)^2/2) exp[-\omega^2 (t - t_0)^2/4]$ with dominated frequency $f_0 = 150$ Hz ($\omega = 2\pi f_0$) and pulse delay $t_0 = 2/f_0$.

Figure 2 shows snapshots of the wave field simulation for a homogeneous poroelastic medium taken at time $t = 0.1$ seconds for different porosities $\phi = 0, \phi = 0.5$ and $\phi = 1$.

As can be seen from the plots in Fig. 2, the wave field varies significantly depending on the porosity of the medium. In the case of porosity $\phi = 1$ we have a pure liquid medium. In such a medium there is only a pressure wave propagating with the velocity of the fluid phase 1500 m/s. In the case of porosity $\phi = 0$ we have a pure elastic medium with a longitudinal and a shear wave propagating with velocities of 3800 m/s and 2400 m/s respectively. And in the case of porosity $\phi = 0.5$, together with longitudinal and shear waves, we see the appearance of a slow Biot wave in the poroelastic medium. The velocity of these waves depends on the frequency of the signal at the source and can be estimated using dispersion curves.

The next step was to perform a series of numerical simulations to estimate the quality factor Q (Q-factor). Several approaches are known to estimate the Q-factor, expressing the value in terms of elastic moduli, energies, spatial attenuation coefficient, phase delay between stress and strain, signal amplitude, etc. [19]. Since in our experiment we perform wave propagation and have the possibility to record the signal by receivers, we adopt a signal deconvolution approach [20]. Considering two receivers at points $y = y_1$ and $y = y_2$ located on the same vertical line passing through the source, we obtain two traces for P-waves propagating over the distance d_0 and $d_0 + d$. We consider the signal propagating at the receiver closer to the source to be of the form $u_1 = u_0 e^{i\omega(t - y_1/c(\omega))}$, where u_0 is the amplitude and $c(\omega)$ is the complex phase velocity. After propagation over the distance d, the expression for the wave takes the form $u_2 = u_1 e^{i\omega d/c(\omega)}$. The transition to the frequency domain using the Fourier transform is applied to the signals u_1 and u_2 to deconvolve them by the ratio u_2/u_1. The components $c(\omega)$ are then obtained from the logarithm of the ratio of the signals, and the quality factor can be estimated by $Q = \lambda Re(c^2)/Im(c^2)$, where λ is the wavelength. In order to obtain an estimate that is independent of the distance between the two receivers, a multiplication by the wavelength is carried out.

Calculations were carried out for different values of porosity and different values of relaxation time. The results are shown in Figs. 3-7. Figure 3 shows the estimation of the Q-factor for a purely elastic medium with porosity $\phi = 0$ and for different relaxation times τ. The estimation is performed for the seismic frequency range 70–300 Hz. The graph shows that for all relaxation times considered, the Q-factor is the same and equal to the constant 560. This value corresponds to a medium in which there is practically no attenuation.

The situation changes when the medium becomes porous. Figures 4-7 show the evaluation of the Q-factor for the medium with different porosities $\phi = 0.8$, $\phi = 0.5$, $\phi = 0.2$, $\phi = 0$. Since we do not have data on the dependence of the relaxation time on the porosity, a series of calculations were made for each porosity and for different relaxation times $\tau = \infty$, $\tau = 0.1$, $\tau = 0.05$, $\tau = 0.01$, $\tau = 0.005$.

Comparing the graphs, it can be seen that for porous media the relaxation time τ begins to play a significant role in the magnitude of seismic wave attenuation. Simultaneously, the analysis of the numerical results confirms that system (1) ensures the consistency of the Q-factor in the seismic frequency range for all porosity and relaxation time values.

Note that τ in system (1) is very similar to the τ parameter in the τ-method used to simulate the behaviour of viscoelastic materials in viscoelastic models such as the Standard Linear Solid (SLS) and the Generalised Standard Linear Solid (GSLS) models [21,22]. In the τ-method, this parameter characterises the time-dependent response of viscoelastic materials to applied stress and is introduced to save memory, replacing the need to introduce stress and strain relaxation times separately for each of the P and S waves in the SLS and GSLS models.

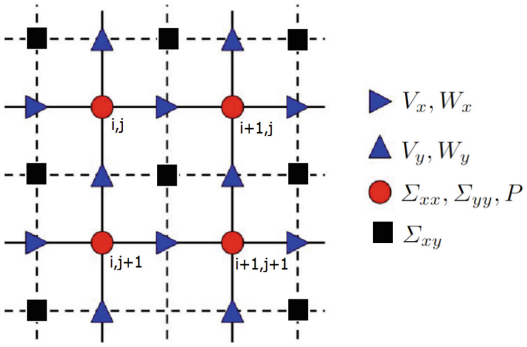


Fig. 1. The relative position of deviatoric stresses, pressure, mixture velocities and relative velocities on the staggered grid.

Table 1. Material parameters of the media.

State	Parameter	Notation	Value	Unit
Solid phase	Longitudinal sound velocity	V_p	3800	m/s
	Shear sound velocity	V_s	2400	m/s
	Density	ρ_2	2500	kg/m^3
Fluid phase	Longitudinal sound velocity	V_p	1500	m/s
	Shear sound velocity	V_s	0	m/s
	Density	ρ_2	1040	kg/m^3
Dissipative parameters	Interphase friction	$c_1^0 c_2^0/\theta_2$	–	s^{-1}
	Relaxation time	τ	10^{-2}	s

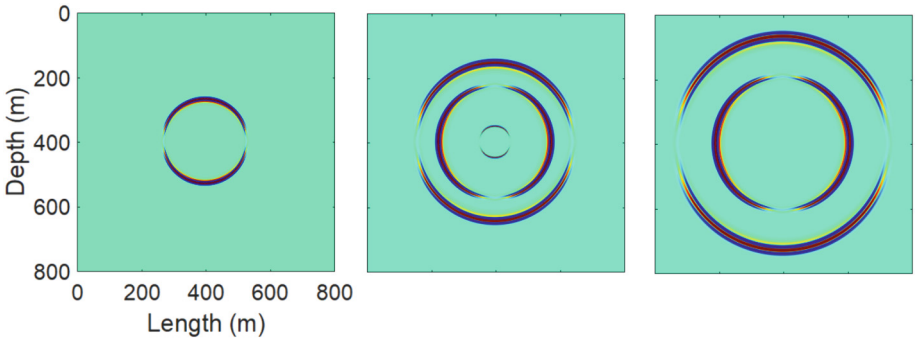


Fig. 2. Snapshot of the mixture velocity component $u2$, recorded for relaxation time $\tau = \infty$ and porosity $\phi = 1$ (left), $\phi = 0.5$ (middle), $\phi = 0$ (right) at time 0.1 s.

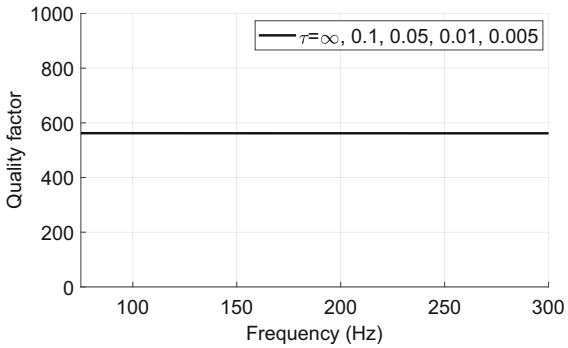


Fig. 3. Compare Q-factor for porosity $\phi = 0$ and different relaxation times in seismic frequency band 70–300 Hz.

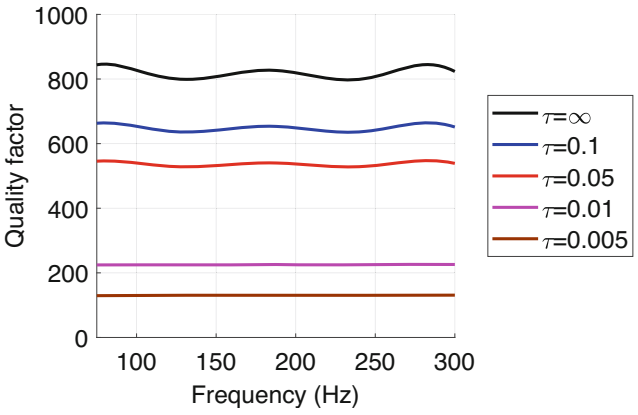


Fig. 4. Compare Q-factor for porosity $\phi = 0.8$ and different relaxation times in seismic frequency band 70–300 Hz.

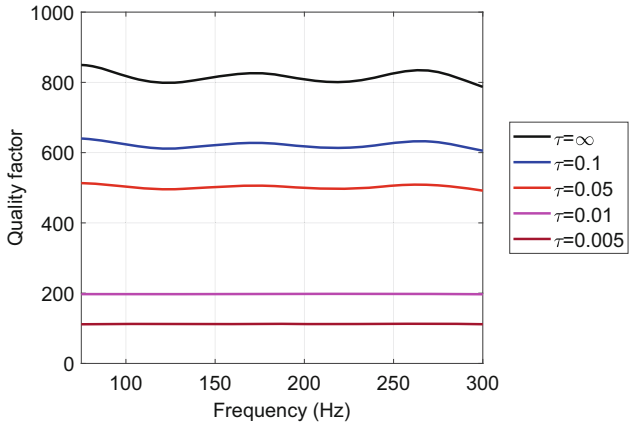


Fig. 5. Compare Q-factor for porosity $\phi = 0.5$ and different relaxation times in seismic frequency band 70–300 Hz.

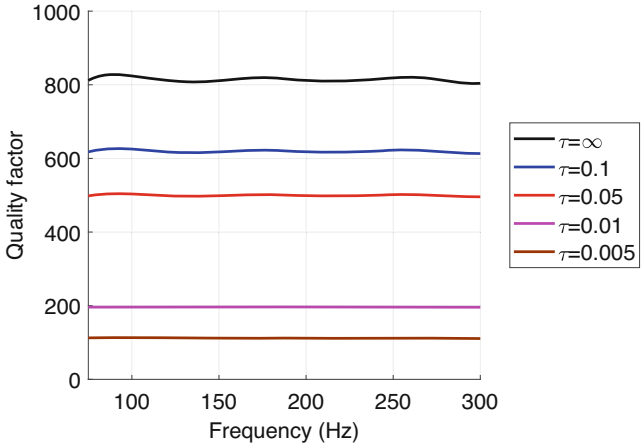


Fig. 6. Compare Q-factor for porosity $\phi = 0.2$ and different relaxation times in seismic frequency band 70–300 Hz.

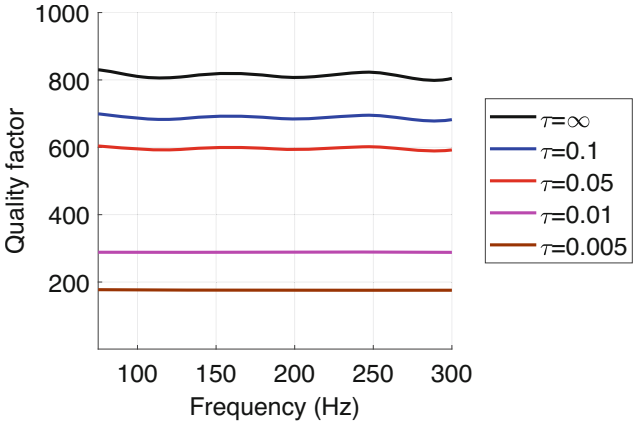


Fig. 7. Compare Q-factor for porosity $\phi = 1$ and different relaxation times in seismic frequency band 70–300 Hz.

5 Conclusions

To study the effect of temperature changes on wave fields during permafrost thawing, a Symmetric Hyperbolic Thermodynamically Compatible (SHTC) model of a saturated porous medium is used, designed to describe the propagation of small amplitude waves. The efficient finite difference method on staggered grid is applied to solving a series of two-dimensional test problems. Although all material parameters in the governing equations may depend on temperature variations, it is shown numerically that wave attenuation and energy dissipation are mainly caused by the dependence of the relaxation time of shear stresses on porosity, the growth of which is due to the thawing of permafrost with a change in temperature. To estimate the energy dissipation during seismic waves propagation the quality factor is used. Since there is no data on the dependence of shear stress relaxation time on porosity, a series of calculations were carried out for different values of porosity and relaxation time. It is concluded that an increase in porosity, accompanied by a decrease in relaxation time, leads to an increase in the quality factor, that is, it increases the absorption of seismic waves. This fact may be the basis for the development of seismic methods for monitoring permafrost thawing.

References

1. Guillemot, A., et al.: Seismic monitoring in the Gugla rock glacier (Switzerland): ambient noise correlation, microseismicity and modelling. Geophys. J. Int. **221**(3), 1719–1735 (2020)
2. Albaric, J., Kühn, D., Ohrnberger, M., Langet, N., Harris, D., Polom, U., et al.: Seismic monitoring of permafrost in Svalbard Arctic Norway. Seismological Res. Lett. **92**(5), 2891–2904 (2021)

3. Steinmann, R., Hadziioannou, C., Larose, E.: Effect of centimetric freezing of the near subsurface on Rayleigh and Love wave velocity in ambient seismic noise correlations. Geophys. J. Int. **224**(1), 626–636 (2021)
4. Biot, M. A.: Theory of propagation of elastic waves in fluid-saturated porous solid. I. Low-frequency range. J. Acoust. Soc. Am. **28**(2), 168–178 (1956)
5. Biot, M. A.: Theory of propagation of elastic waves in a fluid-saturated porous solid. II. Higher frequency range. J. Acoust. Soc. Am. **28**(2), 179–191 (1956)
6. Carcione, J.M., Morency, C., Santos, V.: Computational poroelasticity - a review. Geophysics **75**(5), 75A229-75A243 (2010)
7. Romenski, E., Reshetova, G., Peshkov, I., Dumbser, M.: Modeling wavefields in saturated elastic porous media based on thermodynamically compatible system theory for two-phase solid-fluid mixtures. Comput. Fluids **206**, 104587 (2020)
8. Reshetova, G., Romenski, E.: Diffuse interface approach to modeling wavefields in a saturated porous medium. Appl. Math. Comput. **398**, 125978 (2021)
9. Godunov, S.K., Romenskii, E.I.: Elements of continuum mechanics and conservation laws. Springer, New York, NY (2003). https://doi.org/10.1007/978-1-4757-5117-8
10. Romenski, E.: Hyperbolic systems of thermodynamically compatible conservation laws in continuum mechanics. Math. Comput. Modell. **28**, 115–130 (1998)
11. Peshkov, I., Pavelka, M., Romenski, E., Grmela, M.: Continuum mechanics and thermodynamics in the Hamilton and the Godunov-type formulations. Continuum Mech. Thermodyn. **30**, 1343–1378 (2018)
12. Romenski, E., Reshetova, G., Peshkov, I.: Computational model for compressible two-phase flow in deformed porous medium. In: Gervasi, O., et al. (eds.) ICCSA 2021. LNCS, vol. 12949, pp. 224–236. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-86653-2_16
13. Romenski, E., Reshetova, G., Peshkov, I.: Two-phase hyperbolic model for porous media saturated with a viscous fluid and its application to wavefield simulation. Appl. Math. Model. **106**, 567–600 (2022)
14. Carcione, J.M., Kosloff, D., Kosloff, R.: Wave propagation simulation in a linear viscoacoustic medium. Geophys. J. Int. Geophys. **93**(2), 393–401 (1988)
15. Virieux, J.: P-SV wave propagation in heterogeneous media: velocity-stress finite-difference method. Geophysics **51**(1), 889–901 (1986)
16. Graves, R.W.: Simulating seismic wave propagation in 3D elastic media using staggered- grid finite differences. Bull. Seismol. Soc. Am. **86**(4), 1091–1106 (1996)
17. Samarskii, A.A.: The theory of difference schemes. CRC Press, Boca Raton (2001)
18. Moczo, P., Kristek, J., Vavrycuk, V., Archuleta, R.J., Halada, L.: 3d heterogeneous staggered-grid finite-difference modeling of seismic motion with volume harmonic and arithmetic averaging of elastic moduli and densities. Bull. Seismol. Soc. Am. **92**(8), 3042–3066 (2002)
19. Mavko, G., Mukerj, T., Dvorkin, J.: The Rock Physics Handbook, 2nd edn. Cambridge University Press, Cambridge (1999)
20. Caspari, E., et al.: Attenuation mechanisms in fractured fluid-saturated porous rocks: a numerical modelling study. Geophys. Prospect. **67**(4), 935–955 (2019)
21. Blanch, J., Robertsson, O., Symes, W.: Modeling of a constant Q: methodology and algorithm for an efficient and optimally inexpensive viscoelastic technique. Geophysics **60**, 176–184 (1995)
22. Hestholm, S., et al.: Quick and accurate Q parameterization in viscoelastic wave modeling. Geophysics **71**(5), T147–T150 (2006)



Simulated Annealing Algorithm for Model Reconstruction of the Four-Layer Medium with Elliptical Inclusion in the Third Layer

Dmitry Prokhorov[1(✉)], Galina Reshetova[2], and Denis Bratchikov[3]

[1] Sobolev Institute of Mathematics SB RAS, 4 Koptug Avenue, 630090 Novosibirsk, Russia
prokhorovdi@ipgg.sbras.ru

[2] Institute of Computational Mathematics and Mathematical Geophysics SB RAS, 6 Lavrentev Avenue, 630090 Novosibirsk, Russia
kgv@nmsf.sscc.ru

[3] Novosibirsk State University, 2 Pirogova Street, 630090 Novosibirsk, Russia
d.bratchikov@g.nsu.ru

Abstract. The paper presents an approach for reconstructing the properties of two-dimensional viscoelastic medium with defined geometry using the simulated annealing algorithm. The inverse problem solution requires a lot of computational resources because the direct seismic modeling is performed at each iteration. The staggered grid finite-difference scheme is implemented using CUDA technology to speed up the solution of the direct problem by parallelization. The choice of the simulated annealing method for solving inverse problem is due to the method's ability to avoid local minima of the target functional. However, the simulated annealing method needs a good coverage of the model space by realizations of random probing vectors. It leads to enormous computation time in the case of a four-layer medium with elliptical inclusion in the third layer, which has 37 parameters. Therefore, the sequential reconstruction of model parameters, where the simulated annealing algorithm searches for the parameters in 1 or 2-D subspace, is introduced. Nevertheless, the attenuation properties of medium were not reconstructed by simulated annealing. For their study, the deep convolutional neural network is used.

Keywords: simulated annealing · viscoelastic medium · seismic modeling

1 Introduction

Seismic exploration is one of the advanced tools used to study the internal geological structure of the Earth. The construction of a reliable depth model of the environment is a prerequisite for the search for oil and gas fields. The most important recoverable parameters in the study of hydrocarbon reservoirs are the speed of propagation of seismic waves since it allows us to determine the depth

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 334–351, 2024.
https://doi.org/10.1007/978-3-031-65238-7_23

of rocks and the absorption of seismic energy since it characterizes the fluid saturation of rocks.

In the 20th century, many seismic exploration methods were developed, ranging from reflected and refracted wave methods to various summation and migration procedures. However, in recent years, the requirements for the detail and reliability of predictions obtained during the interpretation of seismic data have increased significantly since the search for new deposits is conducted in areas with complex geological structures. The full waveform inversion method (FWI) [16] is one of the reliable and high-resolution methods used to estimate the parameters of complex medium by the results of measuring wave fields. It solves the inverse dynamic seismic problem by sequential solutions of the direct problem and minimizing the functional discrepancy between the observed and synthetic data. For the first time, the FWI in the time domain using the generalized least squares method was proposed in a series of papers by [1,13]. FWI was developed in the frequency domain [11] to accelerate the inversion. However, FWI has several disadvantages:

1. Ill-posedness of the inverse problem: non-uniqueness of the solution and instability to noisy data.
2. Strong nonlinearity of the target functional—convergence of the method to a local minimum.
3. The sensitivity of the solution to the presence of low-frequency information in seismic data.
4. The presence of the connection between parameters when solving a multiparametric inverse problem leads to incorrect parameter reconstruction.
5. The high computational cost of wave fields computation at each nonlinear least squares method iteration.

Based on the above, when developing an algorithm for restoring the depth model of velocity and attenuation parameters by full wave field, two main areas of optimization are distinguished: the speed of solving a direct problem and the ability of the algorithm to avoid local minima.

A large number of numerical methods are known to solve the problem of seismic wave propagation: the finite difference method [15], the finite volume method [18], the finite element method [2], the spectral element method [7]. The main advantages of the finite difference method include the simplicity of constructing the algorithm and its software implementation, lower computational resource requirements relative to other methods, and the ability to approximate environments of arbitrary geometric complexity with sufficient accuracy for seismic modeling [17]. The algorithms are easily parallelized using CUDA technology, and data exchange between RAM and video memory is minimal.

Global optimization methods can move more freely through the parameter space than gradient descent. Examples include simulated annealing [14], genetic algorithms, and particle swarm optimization [10]. The work of the simulated annealing method [6] is similar to the process occurring during the crystallization of a substance: the algorithm can assume a state with a higher cost than the current one. However, the longer the algorithm works, the lower the 'temperature", i.e., the probability of deciding with a higher cost. Thus, the main

advantage of the simulated annealing algorithm is the possibility of getting out of the local minimum state.

Two tasks have been set as part of the work:

1. To develop and programmatically implement using CUDA technology a finite difference scheme on a staggered grid [15] for a system of viscoelasticity equations.
2. Based on the method of simulated annealing to develop and implement an algorithm for solving the inverse dynamic problem of seismic.

We use the developed algorithm to reconstruct a four-layer medium's geometric and velocity parameters with elliptical inclusion in the third layer. Also, the order of their reconstruction under the condition of limited computing resources is established.

2 Problem Statement

The system of equations describing wave propagation in a two-dimensional isotropic medium with absorption, written in Cartesian coordinates, has the following "velocity-stress" formulation:

$$\begin{cases} \rho\dfrac{\partial u}{\partial t} = \dfrac{\partial \sigma_{xx}}{\partial x} + \dfrac{\partial \sigma_{xz}}{\partial z} + f(t,x,z), \\ \rho\dfrac{\partial w}{\partial t} = \dfrac{\partial \sigma_{zx}}{\partial x} + \dfrac{\partial \sigma_{zz}}{\partial z} + h(t,x,z), \\ \dfrac{\partial \sigma_{xx}}{\partial t} = (\lambda+2\mu)\dfrac{\partial u}{\partial x} + \lambda\dfrac{\partial w}{\partial z} + \xi_{xx}, \\ \dfrac{\partial \sigma_{zz}}{\partial t} = \lambda\dfrac{\partial u}{\partial x} + (\lambda+2\mu)\dfrac{\partial w}{\partial z} + \xi_{zz}, \\ \dfrac{\partial \sigma_{xz}}{\partial t} = \dfrac{\partial \sigma_{zx}}{\partial t} = \mu\left(\dfrac{\partial u}{\partial z} + \dfrac{\partial w}{\partial x}\right) + \xi_{xz}, \\ \dfrac{\partial \xi_{xx}}{\partial t} + \dfrac{1}{\tau_\sigma}\xi_{xx} = (\Lambda+2M)\dfrac{\partial u}{\partial x} + \Lambda\dfrac{\partial w}{\partial z}, \\ \dfrac{\partial \xi_{zz}}{\partial t} + \dfrac{1}{\tau_\sigma}\xi_{xx} = \Lambda\dfrac{\partial u}{\partial x} + (\Lambda+2M)\dfrac{\partial w}{\partial z}, \\ \dfrac{\partial \xi_{xz}}{\partial t} + \dfrac{1}{\tau_\sigma}\xi_{xx} = M\left(\dfrac{\partial u}{\partial z} + \dfrac{\partial w}{\partial x}\right), \end{cases} \tag{1}$$

where $\boldsymbol{u} = (u, w)$—velocity vector, $\sigma = \begin{pmatrix} \sigma_{xx} & \sigma_{xz} \\ \sigma_{zx} & \sigma_{zz} \end{pmatrix}$—stress tensor, $\xi = \begin{pmatrix} \xi_{xx} & \xi_{xz} \\ \xi_{zx} & \xi_{zz} \end{pmatrix}$—memory variables, ρ—constant density, $\lambda, \mu, \Lambda, M, \tau_\sigma$—coefficients, characterizing the viscoelastic properties of the medium. In this case, the state of the viscoelastic medium $\boldsymbol{u}, \sigma, \xi$ depends on the spatial variables x, z and time t, and the parameters of the medium $\rho, \lambda, \mu, \Lambda, M, \tau$ depend only on spatial variable, the system 1 is defined in the half-plane $z \leq 0$.

For a system of Eqs. 1 the initial boundary value problem is formulated in the half-plane $\boldsymbol{R}^2 z \leq 0$ with zero initial data:

$$\begin{aligned} u|_{t=0} = 0, \quad w|_{t=0} = 0, \\ \sigma_{xx}|_{t=0} = 0, \quad \sigma_{xz}|_{t=0} = 0, \quad \sigma_{zz}|_{t=0} = 0, \end{aligned} \tag{2}$$

and the conditions at the boundary $z = 0$ corresponding to the stress-free surface

$$\sigma_{zz}|_{z=0} = 0, \quad \sigma_{xz}|_{z=0} = 0. \tag{3}$$

The search for a solution is carried out for the time interval $[0, T]$.

For the numerical solution of the initial boundary value problem for a system of Eqs. 1 with initial data 2 and boundary conditions 3, we use a staggered grid scheme [8,15] with second order approximation of finite-difference operators for both spatial and time variables. The finite difference scheme is implemented in C++ using CUDA technology.

3 Formulation of the Inverse Dynamic Seismic Problem

On the free surface $z = 0$ at the specified point $x = x_i (i = 1, ..., N)$ there is a system of receivers recording the coordinates of the velocity vector $\boldsymbol{u}^j(t_k, x_i, 0) = (u_i^j(t_k), w_i^j(t_k))$, $1 \leq i \leq N$, $1 \leq j \leq P$, $1 \leq k \leq K$ at time points t_k corresponding to the j impact on the system. At points $(x_j, 0)$, a Ricker wavelet with a dominant frequency f is applied:

$$R(t) = \left(1 - 2(\pi f(t - \frac{2}{f}))^2\right) e^{-\left(\pi f(t-\frac{2}{f})^2\right)}.$$

The symbol Y_j denotes the vector corresponding to the seismogram for the j impact:

$$Y_j = (u_1^j(t_1), w_1^j(t_1), u_2^j(t_1), w_1^j(t_2), ..., u_1^j(t_2), w_1^j(t_2), ..., u_N^j(t_K), w_1^N(t_K)),$$

and the symbol Y is:

$$Y = (Y_1 \cdot Y_2 \cdot ... \cdot Y_P),$$

where '$\cdot$' is a vector concatenation operation. Thus, Y is a vector of length $2 \times N \times K \times P$. On the vector space of seismograms $\boldsymbol{Y}$, a 2-norm is set ($||x||_2 = \sqrt{x_1^2 + ... + x_{2NKP}^2}$). Next, $\boldsymbol{Y}$ is used to denote the normed vector space of seismograms.

Let us introduce a model of a viscoelastic medium $m = (\rho, \lambda, \mu, L, M, \tau) \in M$ (M—data space) and define the operator of the direct problem $F(m) : M \to \boldsymbol{Y}$, matching the models m vector $F(m) \in \boldsymbol{Y}$, built according to the solution of the system 1 with the parameters m. Then the inverse problem can be formulated as follows [1]:

$$\begin{aligned} \text{Find } \tilde{m} \in M \mid E(\tilde{m}) = \min_{m \in M} E(m), \\ E(m) = ||F(m) - Y_d||, \end{aligned} \tag{4}$$

where Y_d is a vector that corresponds to the seismograms obtained by the observation system.

4 Data Space for a Four-Layer Medium with Elliptical Inclusion in the Third Layer

In general, M is a space of vector functions. However, in the case of a four-layer medium with an elliptical inclusion in the third layer (Fig. 1), the definition domain of the functional F is significantly simplified. Let $(\rho_i, \lambda_i, \mu_i, L_i, M_i, \tau_i)$ denote the parameters of the medium on the i-th layer for $1 \leq i \leq 4$, $i = 5$ corresponds to the parameters of the medium in an elliptical inclusion. The parameters h_1, h_2, h_3 are the thicknesses of the layers, (x_0, y_0)—the center of the ellipse, a, b—its semi-major and semi-minor axes. Thus, the model is completely described by a vector of 37 parameters, each a scalar.

It is more convenient to use another parameterization of the medium model using velocities and relaxation times instead of Lame coefficients [12]:

$$\begin{aligned} \lambda &= \pi_0 \frac{\tau_\epsilon^p}{\tau_\sigma} - 2\mu_0 \frac{\tau_\epsilon^s}{\tau_\sigma},\ \mu = \mu_0 \frac{\tau_\epsilon^s}{\tau_\sigma},\ \tau = \tau_\sigma, \\ \Lambda &= \frac{1}{\tau_\sigma}\left(\pi_0\left(1 - \frac{\tau_\epsilon^p}{\tau_\sigma}\right) - 2\mu_0\left(1 - \frac{\tau_\epsilon^s}{\tau_\sigma}\right)\right), \\ M &= \frac{1}{\tau_\sigma}\mu_0\left(1 - \frac{\tau_\epsilon^s}{\tau_\sigma}\right),\ \mu_0 = \rho V^{s2},\ \pi_0 = \rho V^{p2}. \end{aligned} \tag{5}$$

where τ_σ—stress relaxation time, $\tau_\epsilon^p, \tau_\epsilon^s$—relaxation times of deformations of P- and S-waves, respectively, μ_0—relaxation modulus for S-waves, analogous to the Lame coefficient μ in elasticity, π_0—relaxation modulus for P-waves, analogous to the sum of the Lame coefficients $\lambda + 2\mu$ in elasticity. In the viscoelastic case, V^p and V^s in the parametrization 5 do not coincide with the actual propagation velocities of P and S waves in the medium. Thus, the parameters of the medium in the layer (ellipse) are set by six parameters $(\rho_i, V^p, V^s, \tau_\epsilon^p, \tau_\epsilon^s, \tau_\sigma)$ and the length of the desired vector remains equal to 37. The simulated annealing algorithm is used to find it.

5 The Use of the Simulated Annealing Algorithm for Solving the Inverse Dynamic Seismic Problem

The minimum is searched in the rectangular subdomain M_{sa} of the space M. The subdomain M_{sa} is defined by vectors of upper and lower bounds:

$$\begin{aligned} m^u &= (\rho_1^u, \lambda_1^u, ..., a^u, b^u), \\ m^l &= (\rho_1^l, \lambda_1^l, ..., a^l, b^l), \\ M_{sa} &= [\rho_1^l, \rho_1^u] \times [\lambda_1^l, \lambda_1^u] \times ... \times [a^l, a^u] \times [b^l, b^u]. \end{aligned}$$

The vectors of the upper and lower bounds are selected based on some a priori estimates of the medium parameters.

Description of the simulated annealing algorithm in terms of the inverse problem 4:

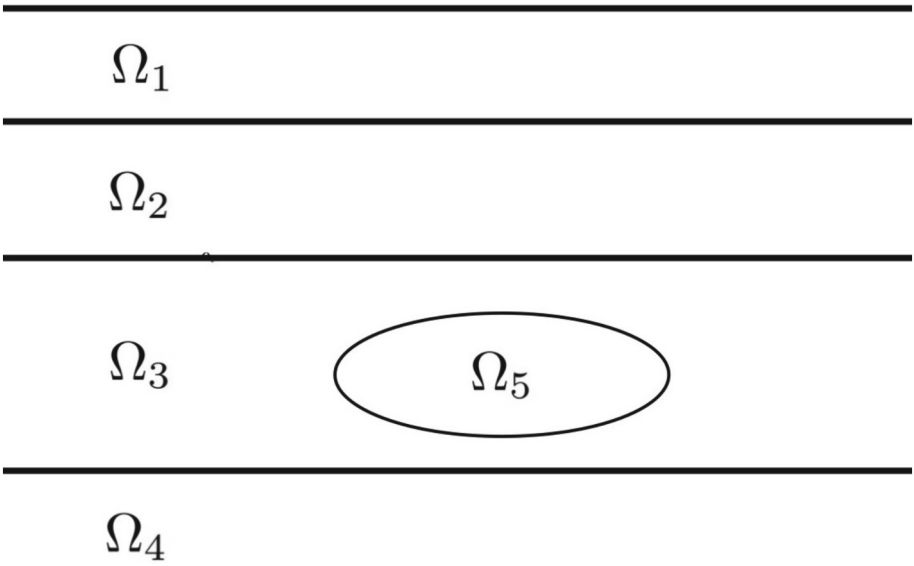


Fig. 1. Four-layer medium with elliptical inclusion in the third layer

1. *Initialization:* calculate the cost of $E(m_1)$ for a random vector of medium parameters $m_1 \in M_{sa}$. Initialize the best state $m_b = m_1$. Assign $k = 0, n = 0$. Set the initial values of the acceptance temperature $T_k^{ac} = T_0^{ac}$ (affects the probability of accepting a state with a higher cost) and the generation temperature $T_k = T_0$ (affects the correlation between the current vector and the probing one).
2. *Generation:* generate a probing vector $m_2 = m_1 + \epsilon$, where $\epsilon = g(T_k)$ is a random variable. In the case of $m_2 \notin M_{sa}$, consider the components of the vector m_2 that go beyond the range to be equal to the corresponding values at the boundary. Find the cost of the probing vector $E(m_2)$.
3. *Acceptance:* Assign $m_1 = m_2$ if $E(m_2) \leq E(m_1)$, otherwise assign $m_1 = m_2$ with probability $A(m_1 \rightarrow m_2, T_k^{ac})$. In the case of $E(m_2) \leq E(m_b)$ assign $m_b = m_2$. Increase $n = n + 1$. If $n < N$, go to step 2, otherwise to step 4.
4. *Temperature decreasing:* reduce temperatures according to schedules $T_{k+1} = U(T_k, k)$, $T_{k+1}^{ac} V(T_k^{ac}, k)$. Assign $m_1 = m_b$, $n = 0$. Increase $k = k + 1$. If $k < K$, go to step 2. Otherwise, the algorithm terminates with the best state of m_b.

Schedules U, V, distribution g, and probability of acceptance A are the algorithm's parameters. The following expressions are used to solve the inverse problem:

$$A(m_1 \rightarrow m_2, T_k^{ac}) = \exp\left(-\frac{E(m_2) - E(m_1)}{T_k^{ac}}\right),$$

$$U(T_k) = \alpha T_k, V(T_k^{ac}) \quad = \alpha^{ac} T_k^{ac}.$$

$$g(T_k) = (\epsilon_1 \epsilon_2 T_k, ..., \epsilon_1 \epsilon_2 T_k),$$

where ϵ_1 is a random variable taking the value 1 with probability p and the value 0 with probability $1 - p$, ϵ_1 is a random variable with a standard normal distribution. The ability to use the same expressions for all components of the vector ϵ is achieved by normalizing the search ranges of the components of the vector m.

The algorithm has seven parameters:

1. N—the number of iterations of the inner loop.
2. K—the number of iterations of the outer loop.
3. T_0—generation temperature.
4. T_0^{ac}—acceptance temperature.
5. α— the decrease "rate" of the generation temperature.
6. α^{ac}—the decrease "rate" of the acceptance temperature.
7. p—the probability of changing the component of the current state when generating a probing solution.

The algorithm takes a vector of upper and lower bounds as input. The output is the vector $m_b \in \Omega_{sa}$ with the lowest cost $E(m_b) \leq (m)$, among all vectors $m \in \Omega_{sa}$ tested by the algorithm.

6 Medium Parameters Reconstruction

The simulated algorithm belongs to the group of Monte Carlo methods. Therefore, to accurately restore the model parameters, the probing vectors must cover the domain Ω_{sa} good enough. For example, if the probing vectors are not random but located in nodes of a uniform grid with ten nodes for each dimension, then 10^{37} solutions to the direct problem would be required. Carrying out such many calculations in practice is impossible in the current state of computing technologies.

Based on the simulated annealing algorithm analysis, it was found to primarily restore the model's most significant (in terms of error E) parameters. Example: the Rayleigh wave makes the most significant error, the speed of which depends on the speed of the S-wave in the first layer. Therefore, we assume that the model parameters can be found sequentially.

As a result of solving a series of inverse problems, it was found that the developed algorithm cannot restore the parameters ρ_i. For known density values, the algorithm restores the values of the relations $\frac{\tau_\epsilon^p}{\tau_\sigma}$ and $\frac{\tau_\epsilon^s}{\tau_\sigma}$, but not the absolute value of τ_σ. At an unknown density, restoring the ratio of relaxation times is impossible. Therefore, when solving a model problem, the medium is assumed to be elastic, and $\rho = const$ in the entire computational domain.

In order to find the upper and lower boundaries of the search and determine the hierarchy of the model parameters, seismograms are analyzed by the researcher. The coordinates of the center of the ellipse along the x axis are found by analyzing the zero-offset seismogram (Fig. 2). The flat boundaries of

the layers give straight lines of reflections at zero-offset; the arcs correspond to reflections from the ellipse. Their center of symmetry is $x = 2600$—the center of the ellipse. A seismogram recorded for the source $x = 4000$ (Fig. 3) is used to restore the parameters of the layers, and to restore the geometric parameters of the inclusion, a seismogram recorded for the source $x = 2600$ (Fig. 4), that is, when calculating the cost of E, only one seismogram is used in each experiment.

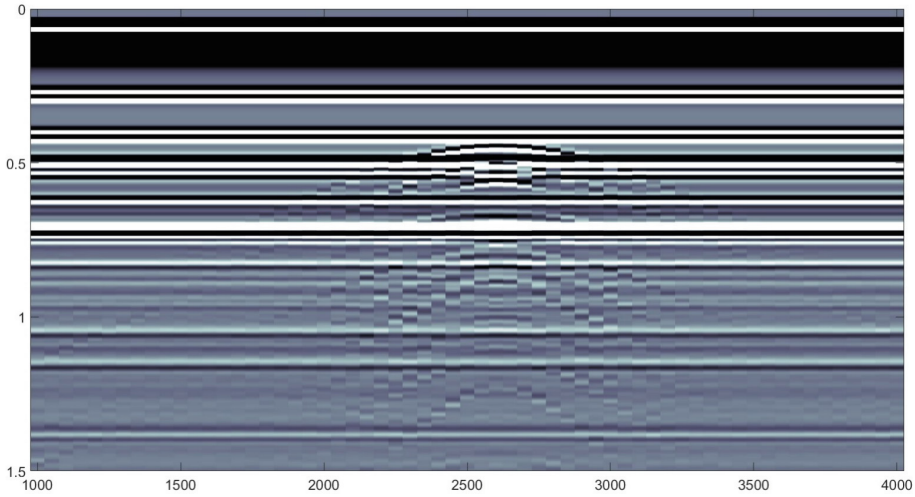


Fig. 2. Zero-offset seismogram

In order to restore the parameters of the medium, eight numerical experiments were performed. The parameters of the simulated annealing algorithm for each of them are shown in the Table 1.

Table 1. Parameters of the simulated annealing algorithm for eight numerical experiments

Number	N	K	T_0	T_0^{ac}	α	α^{ac}	p
1	10	3	0.15	0.5	0.5	0.25	1
2	10	3	0.15	0.5	0.5	0.25	1
3	15	3	0.15	0.5	0.5	0.25	1
4	20	3	0.15	0.05	0.5	0.25	1
5	30	3	0.15	0.5	0.5	0.25	1
6	20	2	0.15	0.05	0.5	0.25	1
7	30	3	0.15	0.05	0.5	0.25	1
8	100	2	0.15	0.05	0.5	0.25	1

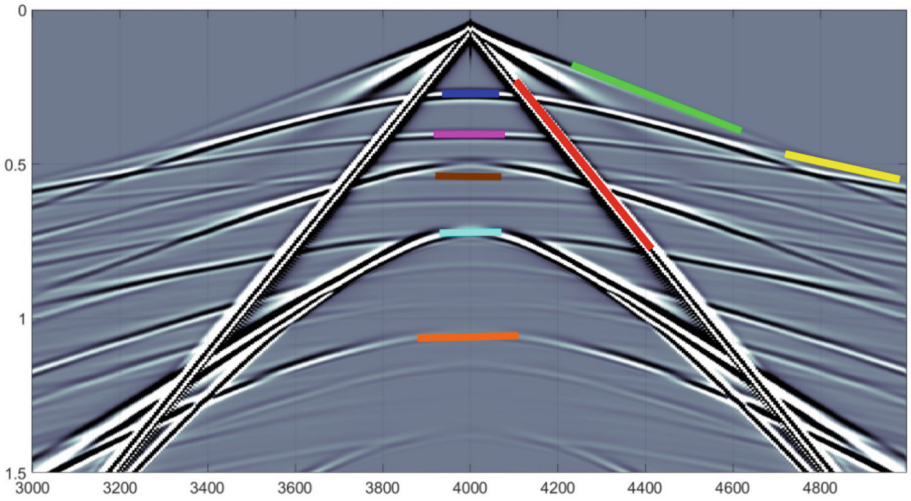


Fig. 3. Seismogram for a source with offset 4000 m. Red—Rayleigh wave. Green—direct P-wave. Blue—P-wave reflected from the second layer. Yellow—P-wave refracted by the second layer. Magenta—P-wave reflected from the third layer. Cyan—S-wave reflected from the second layer. Orange—S-wave reflected from the third layer. Brown—P-wave reflected from the fourth layer (Color figure online).

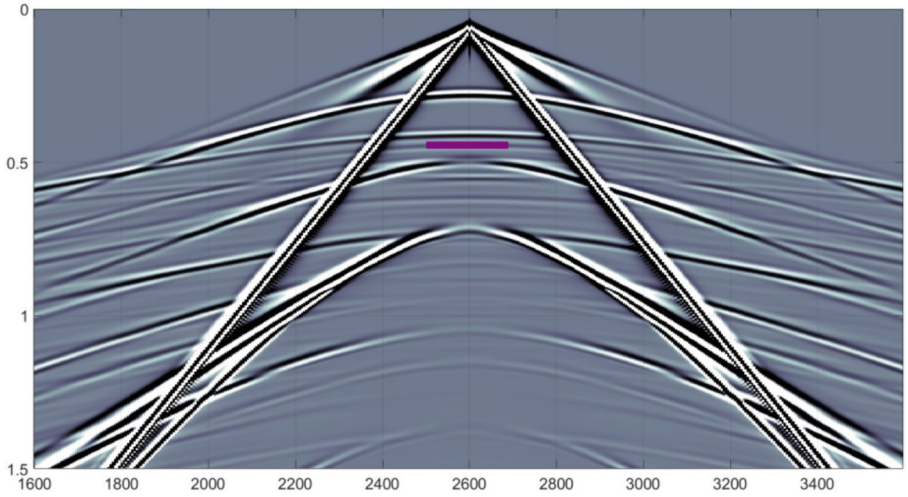


Fig. 4. Seismogram for a source with offset 2600 m. Purple—P-wave reflected from the ellipse top boundary (Color figure online).

The parameters of the finite-difference scheme for solving the direct problem for each numerical experiment are given in the Table 2. The width of the absorbing layers is 20 points.

Table 2. Parameters of a finite-difference scheme for solving a direct problem for eight numerical experiments

Number	N_x	N_z	h_x (m)	h_z (m)	τ (s)	T (s)
1	2201	200	1	1	0.0001	0.35
2	2201	300	1	1	0.0001	0.35
3	2201	300	1	1	0.0001	0.35
4	2201	500	1	1	0.0001	0.45
5	2201	500	1	1	0.0001	1.5
6	2201	850	1	1	0.0001	0.7
7	2201	850	1	1	0.0001	0.5
8	2201	850	1	1	0.0001	0.7

Step 1. Constant values are set for calculations: $\rho = 1500, \tau_\sigma = \tau_\epsilon^p = \tau_\epsilon^s = 0.005$. The dominant frequency of the Ricker wavelet is calculated $f = 30$ Hz.

Step 2. The approximate value of the Rayleigh wave velocity is found by the slope coefficient k_1 of the line 1 (Fig. 3).

$$V^r = \frac{1}{k_1} = 565.$$

It is assumed that the velocity of the S-wave on the first layer is close to the velocity of the Rayleigh wave. Therefore, visual analysis of seismograms fails to establish a line corresponding to the S-wave.

Similarly, the approximate value of the velocity of the P-wave in the first layer is found by the slope coefficient k_2 of the line 2 (Fig. 3).

$$V_1^{p,init} = \frac{1}{k_1} = 1840.$$

The found velocity values are used as an approximate model of the medium and to set the search boundaries in the simulated annealing algorithm.

Experiment 1. Reconstruction of the first layer S-wave velocity. Medium model: homogeneous medium, P-wave velocity—$V_1^{p,init}$, S-wave velocity V_1^s—unknown parameter. The subdomain of the seismogram is involved in calculating E: $t \leq 0.35$. The search range of the simulated annealing algorithm is $V_s^1 \in [V^r, 1.1V^r]$. Found value: $V_1^s = 603$.

Experiment 2. Reconstruction of the first layer P-wave velocity. Medium model: homogeneous medium, P-wave velocity—unknown parameter, S-wave velocity—V_1^s. The subdomain of the seismogram is involved in calculating E: $t \leq 0.5$ with a Rayleigh wave cut out. Search range: $V_1^p \in [0.9V_1^{p,init}, 1.1V_1^{p,init}]$. Found value: $V_1^p = 1874$.

Step 3. The measured arrival time of the reflected P-wave from the second layer (curve 3, Fig. 3) is 0.277. The start time t_0 of the source's impact on the medium is assumed to be 0.077. Therefore, the doubled time of the P-wave run through the first layer $t_1 = 0.277 - 0.77 = 0.2$. The time t_1 is used to estimate the thickness of the first layer $h_1 = \frac{t1}{2} V_1^p = 187$. Also, based on the slope of the refracted wave, the velocity of the P-wave in the second layer is estimated using the formula 6

$$h_1 = \frac{t_{ref} V_2^p V_1^p}{2((V_2^p)^2 - (V_1^p)^2)^{1/2}},$$
$$V_2^p = \sqrt{\frac{(V_1^p)^2}{1 - \frac{t_{ref}^2}{4h_1^2}(V_1^p)^2}}, \tag{6}$$

where $t_{ref} = 0.156$—the time-coordinate of intersection of line 4 (Fig. 3) with the line $x = 4000$. Therefore, the value of the P-wave velocity on the second layer is estimated as $V_2^p = 2992$. However, attempts to reconstruct V_2^p using simulated annealing were unsuccessful. The algorithm finds $V_2^p \approx .2800$, synthetic seismograms with this value differ from the observed ones. This algorithm's behavior is because attenuation is not considered in this experiment: the amplitude of the refracted wave on the synthetic seismogram significantly exceeds the amplitude of the refracted wave on the observed one. Because of this, the state with a lower cost is where the arrival of the refracted wave coincides with the arrival of the reflection from the third layer (Fig. 5). Therefore, in this experiment, the optimizer is not the simulated annealing algorithm but a researcher who, based on the results of a series of numerical solutions to a direct problem, chooses such a value V_2^p so that the peaks of the amplitudes of reflected waves on synthetic and observed data coincide. Found value: $V_2^p = 3070$.

The measured arrival time of the P-wave reflection from the third layer (curve 5, Fig. 3): 0.411. The doubled travel time of the P-wave through the second layer $t_2 = 0.411 - t1 - t0 = 0.134$.

The values t_1, t_2 and V_2^p are used to restore the thickness of the first and second layers and the velocity of the S-wave in the second layer.

Experiment 3. Reconstruction of the first layer thickness. Medium model: two-layer medium, velocities of the first layer—(V_1^p, V_1^s), thickness of the first layer h_1—unknown parameter, velocities of the second layer—$(V_p^2, \frac{V_2^p}{\sqrt{3}})$. The subdomain of the seismogram is involved in calculating E: $t \leq 0.35$ with a cut Rayleigh wave. Search range: $h_1 \in [0.9\frac{t_1}{2}V_1^p, 1.1\frac{t_1}{2}V_1^p]$.
Found value $h_1 = 199$.

Experiment 4. Reconstruction of the second layer thickness. Medium model: three-layer medium, velocities of the first layer—(V_1^p, V_1^s), thickness of the first layer—h_1, velocities of the second layer —$(V_p^2, \frac{V_2^p}{\sqrt{3}})$, thickness of the second layer h_2—unknown parameter, speed of the third layer—$(1.33V_2^p, \frac{1.33V_2^p}{\sqrt{3}})$. The subdomain of the seismogram is involved in calculating E: $t \leq 0.7$ with a Rayleigh wave cut out. Search range: $h_2 \in [0.9\frac{t_2}{2}V_2^p, 1.1\frac{t_2}{2}V_2^p]$. The found value is $h_2 = 202$.

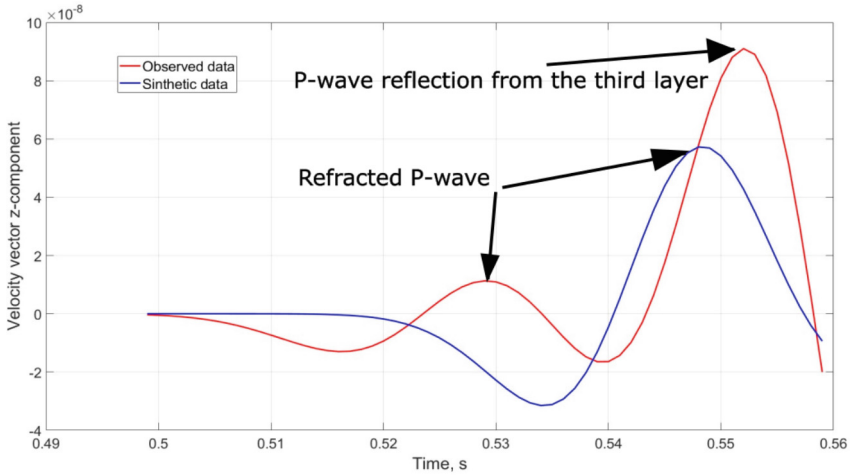


Fig. 5. Trace $x = 3100$ for the source $x = 4000$

Experiment 5. Reconstruction of the the second layer S-wave velocity. Medium model: three-layer medium, velocities of the first layer—(V_1^p, V_1^s), thickness of the first layer—h_1, P-wave velocity on the second layer—V_2^p, S-wave velocity on the second layer V_2^s—the desired parameter, the thickness of the second layer—h_2, the speed of the third layer—$1.33V_2^p$, $\frac{1.33V_2^p}{\sqrt{3}}$). The subdomain of the seismogram is involved in calculating E: the entire seismogram with a cut Rayleigh wave. Search range: $U_1 \in [V_1^s, \frac{V_2^p}{\sqrt{2}}]$. The found value is $V_2^s = 1370$.

Step 4. The measured arrival time of the P-wave reflection from the fourth layer (curve 8, Fig. 3): 0.529. The doubled travel time of the P-wave through the third layer $t_3 = 0.529 - t2 - t1 - t0 = 0.118$. The upper bound of the search for the velocity of the P-wave V^{max} is considered equal to 6000. The P-wave speed in the third layer and the layer thickness are reconstructed in two stages. First, the travel time is specified t_3:

Experiment 6. Refinement of the P-wave travel time in the third layer. Medium model: four-layer medium, speeds of the first layer—(V_1^p, V_1^s), thickness of the first layer—h_1, speeds of the second layer—(V_p^2, V_2^s), thickness of the second layer—h_2, the P-wave velocity in the third layer V_3^p— the desired parameter, the velocity of the S-wave in the third layer—$\frac{1.33V_2^p}{\sqrt{3}}$, thickness of the third layer h_3—unknown parameter, speed of the fourth layer—$(1.1V_{max}, \frac{1.1V_{max}}{\sqrt{3}})$. The subdomain of the seismogram involved in calculating E: $0.5 \le t \le 0.7$ with a Rayleigh wave cut out. Search range: $\frac{h_3}{V_3^p} \in [0.9\frac{t3}{2}, 1.1\frac{t3}{2}]$. The found value is $\frac{h_3}{V_3^p} = 0.0649$.

Then the values of h_3 and V_3^p themselves are found, provided $h_3 = 0.0649V_3^p$

Experiment 7. Reconstruction of the P-wave velocity in the third layer and the thickness of the third layer. Medium model: four-layer medium, speeds of

the first layer—(V_1^p, V_1^s), thickness of the first layer—h_1, speeds of the second layer—(V_p^2, V_2^s), thickness of the second layer—h_2, the velocity of the P-wave in the third layer V_3^p—the desired parameter, the velocity of the S-wave in the third layer—$\frac{1.33V_2^p}{\sqrt{3}}$, thickness of the third layer h_3—unknown parameter, speed of the fourth layer—$(1.1V_{max}, \frac{1.1V_{max}}{\sqrt{3}})$. The subdomain of the seismogram involved in calculating E: $0.5 \leq t \leq 0.7$ with a Rayleigh wave cut out. Search range: $V_3^p \in [V_2^p, V^{max}]$. The values found are $V_3^p = 4707,\ h_3 = 306$.

Step 5. The measured arrival time of the P-wave reflection from the upper boundary of the ellipse (curve 1, Fig. 4): 0.456. The doubled travel time of the P-wave from the boundary of the second layer to the boundary of the ellipse $t_e = 0.456 - t2 - t1 - t0 = 0.045$. Since only the geometric inclusion parameters are restored, the velocities inside the ellipse are set as $V_p^e = 2200, V_s^e = 1200$, corresponding to highly porous sandstone.

It is assumed that the distance from the lower boundary of the ellipse to the fourth layer is at least 5 m, the semi-major axis of the ellipse is parallel to the x axis and does not exceed 1000 m, and the length of the semi-minor axis is at least 10 m.

Experiment 8. Reconstruction of the geometric properties of an elliptical inclusion. Medium model: four-layer medium, speeds of the first layer—(V_1^p, V_1^s), thickness of the first layer—h_1, speeds of the second layer—(V_p^2, V_2^s), thickness of the second layer—h_2, speeds of the third layer—$(V_p^3, \frac{1.33V_2^p}{\sqrt{3}})$, thickness of the third layer—h_3, speeds of the fourth layer—$(1.1V_{max}, \frac{1.1V_{max}}{\sqrt{3}})$, elliptical inclusion velocities—(V_p^e, V_s^e), center of elliptical inclusion —$x = 2600$, coordinate z—unknown parameter, semi-major and semi-minor axes a, b—unknown parameters. The subdomain of the seismogram is involved in calculating E: $t \leq 0.7$ with a Rayleigh wave cut out. Search range: $a \in [\frac{h_3 - \frac{t_4}{2}V_p^3 - 5}{2}, 1000],\ b \in [10, \frac{h_3 - \frac{t_4}{2}V_p^3 - 5}{2}]$. The values found are $a = 98,\ b = 64$, the center of the ellipse—$(2600, 571)$.

In total, the following medium parameters were found (Fig. 6):

- First layer: $V^p = 1874$m/s, $V^s = 603$m/s, $h = 199$m.
- Second layer: $V^p = 3070$m/s, $V^s = 1370$m/s, $h = 202$m.
- Third layer: $V^p = 4707$m/s, $h = 306$m.
- Elliptical inclusion: offset of the ellipse center along the x axis—2600 m, offset of the ellipse center along the z axis—571 m, length of the semi-major axis (parallel to the x axis)—98 m, length of the semi-minor axis—64 m.

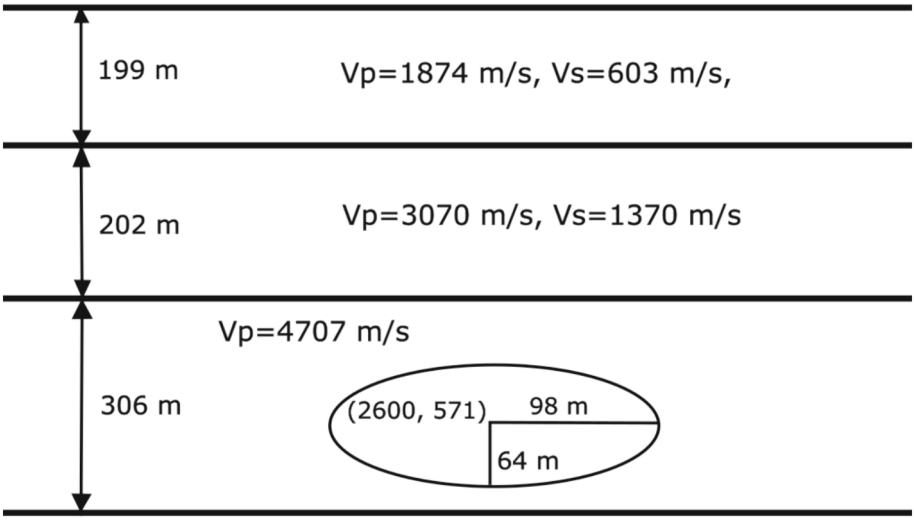


Fig. 6. Reconstructed medium parameters

7 Reconstruction of the Attenuation Parameters of a Viscoelastic Medium Using Deep Learning Methods

Since the simulated annealing algorithm fails to restore the attenuation parameters of the medium, an alternative method for solving the inverse problem based on data is considered. Assuming that there is a data sample that describes the relationship between seismograms and the viscoelastic model of the medium well enough, we can try to reconstruct the operator of the inverse problem F^{-1} using supervised learning on the given data set by minimizing the loss function

$$F_*^{-1} = \arg\min_{F^{-1} \in U} L(m, F^{-1}(d)), \tag{7}$$

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

The approximation of the inverse problem operator F^{-1} is carried out using deep learning methods. A deep convolutional neural network (CNN) is used as an approximator. According to the universal approximation theorem of CN [19], any continuous function of several variables can be approximated by a deep convolutional neural network with any predetermined accuracy. Therefore, if the sample is sufficiently representative, then seismic data mapping into the medium model can be learned with sufficiently high accuracy. After training, the operator $\hat{F}^{-1}$ is used on new seismic data d_{new} to reconstruct the medium model m_{target}.

To translate data from the seismogram space into the model space, a convolutional neural network of the ResNet [3] architecture with a residual block of full preactivation [4] is used. It consists of 18 convolutional blocks that isolate features from input seismograms, residual units that prevent the attenuation of gradients in the learning process, and a fully connected layer that acts as a regression model based on features highlighted by convolutional layers. Each convolutional block consists of a convolutional layer, batch normalization to regularize the learning process, and the activation function ReLU [9] to introduce non-linearity into the approximation of the operator.

Since the thickness of the layers and the velocities of the longitudinal and transverse waves are restored by simulated annealing, deep learning is used only to reconstruct the Q-factors. In order to simplify the learning process, the Q-factors of only the longitudinal waves in the first two layers are reconstructed.

A synthetic training sample of seismograms is prepared by the developed direct problem solver. The velocity and geometric characteristics of the medium are assumed to be equal to the values found by the simulated annealing method. It is assumed that in the first layer, the density of ρ is fixed; its value is— $1500\,\mathrm{kg/m^3}$. In the second and third layers, densities range from $1000\,\mathrm{kg/m^3}$ to $8000\,\mathrm{kg/m^3}$ in $250\,\mathrm{kg/m^3}$ increments. The Q-factor of the longitudinal waves Q_p varies from 10 to 100 in increments of 10 in the first and second layers. The relaxation times for the 5 model are calculated from the Q-factor by the following formulas:

$$\begin{aligned} Q &= \frac{1+\omega^2\tau_\sigma\tau_\epsilon}{\omega(\tau_\epsilon-\tau_\sigma)}, \\ \omega &= 2\pi f. \end{aligned} \tag{8}$$

Q reaches the minima for $\omega = \frac{1}{\sqrt{\tau_\sigma\tau_\epsilon}}$. Then, assuming that $\tau_\sigma \approx \tau_\epsilon$, $\tau_\sigma = \frac{1}{\omega} = 0.0053052$ for $f = 30$ Hz. Therefore,

$$\tau_\epsilon = \tau_\sigma + \frac{2}{Q\omega}. \tag{9}$$

It is assumed that there is no attenuation in the third layer. For each model, seismograms of the vertical u_z and horizontal u_x components of the velocity vector are calculated. Computational domain — rectangle with sides of 2000 m and 450 m, sampling step in space $h_x = h_z = 1$ m, finite difference grid (with PML) contains 2200×500 nodes, sampling step in time $\tau = 0.0001$ s. The point source is at a point with coordinates $x = 1000$ m, $z = 0.5$ m. Source type — expansion center (30 Hz Ricker wavelet). The receivers are on a free surface in 5 m increments (400 receivers). Recording time is 0.45 s with a sampling step of 0.001 s. Thus, 84100 training pairs (d, m) were obtained to restore the Q-factor of longitudinal waves Q_p in the first and second layers according to seismograms u_x, u_z. The calculation time of one seismograms pair is 2 s (NVIDIA RTX 3090 Ti 24 GB), and the calculation time of the entire sample is 47 h.

The data is normalized before training. The seismograms d are trimmed by the values $[-2e^{-7}, 2e^{-7}]$ for u_z, $[-1e^{-7}, 1e^{-7}]$—for u_x. Then, the seismograms

are compressed to size 256×256 and scaled to the segment $[0, 1]$. The m models are also scaled to the $[0, 1]$ segment.

The test sample for evaluating the quality of training consists of 130 seismograms calculated for known models: the density values in the second and third layers in the test sample models have a uniform distribution over the segment $[1000, 8000]$, the Q-values in the first and second layers have a uniform distribution over the segment $[10, 100]$.

The average quadratic error is selected as a loss function for training a neural network.

$$MSE = \frac{1}{N} \sum_{i=1}^{N} \left(m_i^{true} - m_i^{pred} \right)^2, \tag{10}$$

where m_i^{true} is the true model, $m_i^{pred} = F^{-1}(d_i^{true})$ is the predicted model, N is the size of the training dataset.

The search for optimal weights of the neural network is carried out by minimizing the loss function. To minimize the loss function, an optimizer with an adaptive learning rate Adam [5] is selected - an optimization algorithm combining momentum accumulation principles and conservation of the gradient change frequency.

The neural network is trained for 100 epochs with an initial learning rate of 0.01 and a data packet size 32. Every 15 epochs, the learning rate decreases by a factor of 10. The weights obtained at the 34th epoch are chosen as the final weights since they give the smallest error in the test sample—0.7%. Network training over 34 epochs takes 24 h.

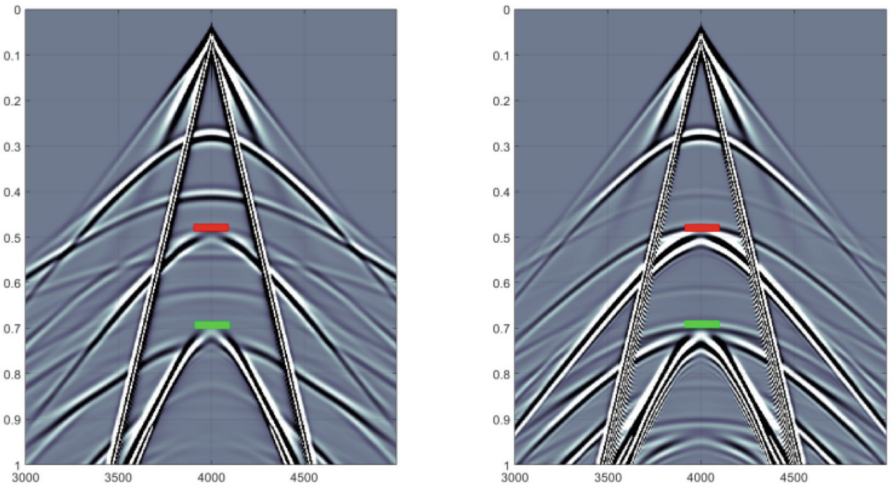


Fig. 7. Seismogram u_z for the source $x = 4000$ (left), seismogram u_z calculated from predicted Q-values (right). Red—the second P-wave reflection from the second layer. Green—the third P-wave reflection from the second layer. (Color figure online)

The trained neural network is applied to the original seismograms for the source $x = 4000$ m, trimmed to $t = 0.45$c. Prediction results: $Q_1^p = Q_2^p = 100$, which can be interpreted as the absence of attenuation in the first and second layers. However, when visually comparing the initial seismograms and seismograms constructed according to the predicted values (Fig. 7), there are differences in attenuation of repeated reflections of the P wave from the boundary of the second layer, which leads to the conclusion that the Q-factor of longitudinal waves in the first layer is significantly lower than predicted.

8 Conclusion

To solve the inverse dynamic seismic problem, an algorithm based on the simulated annealing method has been developed. The algorithm successfully reconstructs the velocity and geometric characteristics of a layered medium with elliptical inclusion in the presence of their approximations. Since numerical experiments have shown that it is impossible to restore the absorbing properties of the medium using the developed algorithm, deep learning methods are used to restore them, namely a convolutional neural network with the ResNet architecture. Although the values predicted by the network seem to differ from the true ones, this approach can give positive results with additional data processing or alternative parameter selection. For example, a Rayleigh wave can be cut from the training sample's seismograms or the seismograms' recording time can be increased so that repeated reflections are observed on the seismograms. However, this will lead to a significant increase in the calculation time of the training sample.

Both proposed approaches are related to the calculation of many direct problems. Therefore, the optimization of the direct problem solver is seen as the most relevant direction for further research. Such optimization requires an excellent scientific base and much experience in parallel computing. A significant advantage here is the use of CUDA technology, which (although this opinion is subjective) is easier to implement and, at the same time, more effective for parallelizing finite difference schemes, compared with parallelization technologies for the CPU (MPI, OMP). Moreover, the memory capacity of modern graphics accelerators makes it possible to use CUDA technology to solve three-dimensional problems without dividing the computing area into several physical nodes, which is a significant advantage in the further solver development.

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

Acknowledgments. The research was supported by the Russian Science Foundation grant no. 19–77-20004.

References

1. Bamberger, A., Chavent, G., Hemon, C., Lailly, P.: Inversion of normal incidence seismograms. Geophysics **47**(5), 757–770 (1982). https://doi.org/10.1190/1.1441345
2. Becache, E., Joly, P., Tsogka, C.: A new family of mixed finite elements for the linear elastodynamic. SIAM J. Numer. Anal. **39**, 2109–2132 (2002)
3. He, K., Zhang, X., Ren, S., Sun, J.: Deep residual learning for image recognition (2015)
4. He, K., Zhang, X., Ren, S., Sun, J.: Identity mappings in deep residual networks. In: Leibe, B., Matas, J., Sebe, N., Welling, M. (eds.) ECCV 2016. LNCS, vol. 9908, pp. 630–645. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-46493-0_38
5. Kingma, D., Ba, J.: Adam: a method for stochastic optimization. Int. Conf. Learn. Representations (2014)
6. Kirkpatrick, S., Gelatt, C.D., Vecchi, M.P.: Optimization by simulated annealing. Science **220**(4598), 671–680 (1983). https://doi.org/10.1126/science.220.4598.671
7. Komatitsch, D., Vilotte, J.P.: The spectral element method; an efficient tool to simulate the seismic response of 2D and 3D geological structures. Bull. Seismol. Soc. Am. **88**(2), 368–392 (1998)
8. Levander, A.R.: Fourth-order finite-difference P-SV seismograms. Geophysics **53**(11), 1425–1436 (1988)
9. Maas, A.L., Hannun, A.Y., Ng, A.Y.: Rectifier nonlinearities improve neural network acoustic models. In: Proceedings of the 30th International Conference on Machine Learning (2013)
10. Mojica, O., Santos, P., Santos, R., Revelo, D.: Building starting models for full-waveform inversion using global optimization methods: a comparison between particle swarm optimization and genetic algorithm (2019). 10.22564/16cisbgf2019.078
11. Pratt, R.G., Shin, C., Hick, G.J.: Gauss-newton and full newton methods in frequency-space seismic waveform inversion. Geophys. J. Int.**133**(2), 341–362 (05 1998). 10.1046/j.1365-246X.1998.00498.x
12. Robertsson, J.O.A., Blanch, J.O., Symes, W.W.: Viscoelastic finite-difference modeling. Geophysics **59**(9), 1444–1456 (1994). https://doi.org/10.1190/1.1443701
13. Tarantola, A.: Inversion of seismic reflection data in the acoustic approximation. Geophysics **49**(8), 1259–1266 (1984). https://doi.org/10.1190/1.1441754
14. Tran, K., Hiltunen, D.: Two-dimensional inversion of full waveforms using simulated annealing. J. Geotech. Geoenvironmental Eng. **138**, 1075–1090 (2012). 10.1061/(ASCE)GT.1943-5606.0000685
15. Virieux, J.: P-SV wave propagation in heterogeneous media: velocity-stress finite-difference method. Geophysics **51**(4), 889–901 (1986)
16. Virieux, J., Operto, S.: An overview of full-waveform inversion in exploration geophysics. Geophysics **74**(6), WCC1–WCC26 (2009)
17. Vishnevsky, D., Lisitsa, V., Tcheverda, V., Reshetova, G.: Numerical study of the interface errors of finite-difference simulations of seismic waves. Geophysics **79**(4), T219–T232 (2014)
18. Zhang, J.: Quadrangle-grid velocity-stress finite-difference method for elastic-wave-propagation simulation. Geophys. J. Int. **131**(1), 127–134 (1997)
19. Zhou, D.: Universality of deep convolutional neural networks. CoRR **abs/1805.10769** (2018)



Reducing Numerical Dispersion in Pseudo-3D Space and Constructing Training Dataset

Elena Gondyul(✉), Kirill Gadylshin, Vadim Lisitsa, and Dmitry Vishnevsky

Institute of Petroleum Geology and Geophysics SB RAS, Koptug Avenue 3, Novosibirsk 630090, Russia
gondyulea@ipgg.sbras.ru

Abstract. The paper discusses the extension of NDM-net (Numerical Dispersion Mitigation neural network) to pseudo-3D cases and the construction of training datasets. NDM-net is initially designed to reduce numerical dispersion in seismic data, which are generated as a result of simulating elastic waves. Previously, seismograms on a coarse grid with numerical dispersion and a certain number of seismograms on a fine grid are calculated to form a training sample. The paper discusses three approaches for building a representative sample to speed up the learning process in case of pseudo-3D. Additionally, the paper discusses the combination of metrics based on statistical analysis.

Keywords: Seismic modelling · Deep learning · Numerical Dispersion

1 Introduction

Numerical dispersion is one of the problems encountered in numerical simulation of seismic fields using a coarse grid to speed up the modeling process. Indeed, seismic modeling requires significant computational memory and is time-consuming, especially when we use it as part of algorithms for processing seismic data [31,32]. This error manifests itself as non-physical reflections arising from the approximation of spatial derivatives in the wave equation. The most common method for solving the system of equations of linear dynamic elasticity theory is the finite difference method on staggered grids [30] and a variation of this scheme that takes into account higher-order approximation in space [14].

Methods such as dispersion suppressing schemes [3,17,18,29], increased approximation order, discontinuous Galerkin method [14,16,22] and spectral element methods [10,24] and so on have problems and limitations, such as reducing the Courant number, tightening stability conditions, increasing the

G. Gondyul performed numerical simulations on NDM-net application, V. Lisitsa suggested the approach to data supression via FFT and D. Vishnevsky performed seismic modelling, K. Gadylshin developed the algorithm to apply the U-net to dispersion suppression under the support of Russian Science Foundation grant no. 22-11-00004.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 352–366, 2024.
https://doi.org/10.1007/978-3-031-65238-7_24

number of floating point operations per grid node, or complex generalization to an elastic medium. Other approaches to this problem are pre- and post-processing [12,19,20]. Such approaches can give fairly accurate results using coarse grids, however, taking into account the same problems that arise, they can be computationally intense.

Another post-processing method is the deep learning approach, which may turn out to be the most productive approach due to its versatility in data processing. This approach extracts the main features from seismograms, thereby extracting nonlinear dependencies between the exact solution and the solution with numerical dispersion. The Numerical Dispersion Mitigation neural network (NDM-net), based on U-net [26], was first proposed in [6], and then developed in [5,7]. Previously, Cycle-GAN (Generative Adversarial Network [8]) training was used in [15] to suppress white noise. [11] uses GAN to overcome the numerical dispersion of wave extrapolation. To suppress white and ground-roll noises, a fully-connected neural network (FCNN) was used in [35]. However, the performance of Deep Learning approaches is deeply depends on the representative sample on which the Neural Network will be trained. Therefore, the paper raises the problem of forming a training sample as the most important one. There are various developed methods of construction, for example, a method for evaluating the quality of a training sample using the output results of the loss function [33], a method RUS (Random under Sampling) using a random forest classifier [34] and t-distributed stochastic neighbor embedding (CAE t-SNE) [23] to analyze the differences between training and target datasets and other. However, such methods do not reveal the properties of the data themselves, in our case, seismograms. Recently, we proposed using three metrics for analyzing seismograms: the distance between sources [6], the distance between seismograms [4], and the distance between velocity models [7]. We used cluster analysis to construct a representative sample. Thus, we took into account the properties of the data itself and with this approach we were able to reduce the training sample without losing the quality of training.

In this paper, we trained the NDM-net on data from pseudo-3D space and built a training sample based on statistical analysis performed to identify the significance of each of the entered metrics.

The rest of the paper is organized as follows. In the Sect. 2, we discuss seismogram modeling, learning strategy, and neural network architecture. The construction of a training sample is discussed in Sect. 3. Numerical experiments are given in Sect. 4.

2 Methodology

2.1 Seismic Modelling

The procedure involves modeling seismic fields using a pseudo-3D acquisition system. The results of this modeling are derived from a stack of 2D modeling results. In order to provide a detailed description of the problem, it is necessary to briefly recall the fundamentals of seismic modeling for the 2D case. Consider

the elastic wave equation written in terms of velocity $\vec{u} = (u_i, u_3)^T$, where $i = 1, 2$, and stress tensor components $\sigma_{ii}, \sigma_{33}, \sigma_{i3}$ and in the Cartesian coordinate system:

$$\begin{array}{l} \rho\frac{\partial u_i}{\partial t} = \frac{\partial \sigma_{ii}}{\partial x_i} + \frac{\partial \sigma_{i3}}{\partial x_3}, \\ \rho\frac{\partial u_3}{\partial t} = \frac{\partial \sigma_{i3}}{\partial x_i} + \frac{\partial \sigma_{33}}{\partial x_3}, \\ \frac{\partial \sigma_{ii}}{\partial t} = (\lambda + 2\mu)\frac{\partial u_i}{\partial x_i} + \lambda\frac{\partial u_3}{\partial x_3} + \hat{f}_{ii}, \\ \frac{\partial \sigma_{33}}{\partial t} = \lambda\frac{\partial u_i}{\partial x_i} + (\lambda + 2\mu)\frac{\partial u_3}{\partial x_3} + \hat{f}_{33}, \\ \frac{\partial \sigma_{i3}}{\partial t} = \mu\frac{\partial u_i}{\partial x_3} + \mu\frac{\partial u_3}{partialx_i} + \hat{f}_{i3}, \end{array} \tag{1}$$

where $\rho = \rho(x_i, x_3)$ is the mass density, $\lambda = \lambda(x_i, x_3)$ and $\mu = \mu(x_i, x_3)$ are the Lame's parameters, and $\hat{f}_{ii} = f_{ii}(t)\delta(x_i - x_i^s)\delta(x_3 - x_3^s)$, $\hat{f}_{33} = f_{33}(t)\delta(x_i - x_i^s)\delta(x_3 - x_3^s)$, $\hat{f}_{i3} = f_{i3}(t)\delta(x_i - x_i^s)\delta(x_3 - x_3^s)$ are the seismic moments tensor. The time wavelet $f_{ii}(t), f_{33}(t), f_{i3}(t)$ are defined be a band-limited impulse. Herewith, the Kronecker's delta function $\delta(x_i - x_i^s)$ consider as the point sources, where (x_i^s, x_3^s) is the source location coordinates.

An important note will be the data collection system, since this is the designation that will be used. The data collection system includes, firstly, two types of lines: along the x_1 coordinate with $x_2 = const$ called inline and along the x_2 with $x_1 = const$ called crossline. The inline includes a set of sources with coordinates $(x_1^s, (x_2^s)_k, 0)_p$, $k = 1, ..., N_2^s$, $p = 1, ..., N_1^s$, where N_2^s is the number of sources along the x_2 direction and N_1^s is the number of sources along the x_1 direction, and a set of receivers with coordinates $(x_1^r(x_1^s)_j, (x_2^s)_k, 0), j = 1, ..., N_1^r$. The crossline includes a set of sources with coordinates $((x_1^s)_k, x_2^s, 0)_p$, $k = 1, ..., N_1^s$, $p = 1, ..., N_2^s$, and a set of receivers with coordinates $((x_1^s)_k, x_2^r(x_2^s)_j, 0), j = 1, ..., N_2^r$. Further,the number of sources in the inline and crossline data matches: $N^s = N_1^s = N_2^s$.

It is convenient to introduce the offset coordinate $(x_1)_o^j = (x_1^r)_j - x_1^s$ for inline and $(x_2)_o^j = (x_2^r)_j - x_2^s$ for crossline, then for all source positions the offset coordinates change within the fixed interval $(x_1)_o \in [-(L_1)_o, (L_1)_o]$, where $(L_1)_o$ is the maximal offset for inline, and $(x_2)_o \in [-(L_2)_o, (L_2)_o]$, where $(L_2)_o$ is the maximal offset for crossline. Thus, we consider the solutions of the system (1) for each source, called seismogramms $\vec{u}(t, (x_i)_o, (x_i)_s^k), i = 1, 2$, as data that we will use in this study. Next, we will denote $\vec{u} = \vec{u}(t, \vec{r}_o, \vec{r}_s^k) = (\vec{u}(t, (x_1)_o, (x_1)_s^k), \vec{u}(t, (x_2)_o, (x_2)_s^k))$ as a solution for the k source.

2.2 Workflow of the Training the NDM-Net

Here, an algorithm for suppressing numerical dispersion based on the features of seismic modeling is described, when solutions are calculated for several right-hand sides, i.e. sources.

At the beginning, the entire set of seismograms $X = \{\vec{u}_{h_2}\}_{i=0}^{N^s}$, where N^s is the number of sources in acquisition system, is modeled on a coarse grid with characteristic grid step h_2, which can be performed relatively quickly. Next, a set of source indexes $D \subset \{1, ..., N^s\}$ is formed. Using D, seismograms $Y = \{\vec{u}_{h_1}\}_k$, $k \in D$ are modeled on a fine grid with characteristic grid step $h_1 < h_2$.

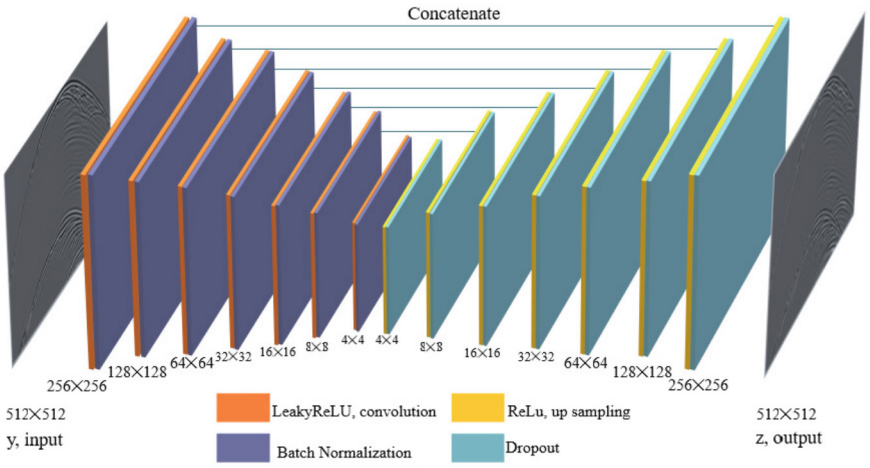


Fig. 1. NDM-net architecture

Thus, we have formed a set consisting of pairs $\{X, Y\}_k$, $k \in D$, which is then used to train the NDM-net. After the network has been trained, we translate all seismograms calculated on a coarse grid into seismograms with suppressed numerical dispersion.

2.3 Data Compression

For efficient performance of the convolution operation during training and simplification of the representation of seismograms, we used the Fast Fourier Transform (FFT). After the conversion, we take only the positive part of the spectrum and throw out low-frequency information that represents only noise. This approach is also used in various tasks, for example, data interpolation based on FFT [13], pseudo-spectral solution of one-way wave equation [24,25].

2.4 NDM-Net

Here, we will briefly describe the Numerical Dispersion Mitigation neural network (NDM-net). We used U-shaped network based on U-net architecture [26] as shown in Fig. 1. And includes 8 downsampling layers with convolution operations, activation function $ReLU(\cdot) = \max(0, \cdot)$ and 8 upsampling layers with deconvolution operations and $LeakyReLU(\cdot) = \max(1, \cdot) + c\min(1, \cdot)$ as an activation function with slope factor $c = 0.2$.

During the training the loss function is minimized:

$$L(\Theta) = \mathbf{E}_{l \in S_t} \left[\| \vec{u}_{h_1} - F\left[\vec{u}_{h_2}, \Theta\right] \|_1 \right],$$

where $F : \vec{u}_{h_2} \rightarrow \vec{u}_{h_1}$ is the operator represented by a multilayer perceptron, $\Theta = \{\mathbf{W}, \mathbf{b}\}$ is the network parameters, which includes the weight matrix $\mathbf{W}$ and bias $\mathbf{b}$, $\mathbf{E}_{l \in S_t}$ is a mean over the training dataset.

It is obvious that a different network architecture can be promising in seismic data processing. For example, Jia et al. [9] suggests using a cascade of dense U-net for denoising images, Yu et al. [35] uses deep convolutional neural network for denoising and ground-roll attenuation of seismic data and Oliveira et al. [21] uses cGan for interpolation of seismic data. However, the purpose of this work was to see how to construct an optimal training sample.

We used two NVIDIA GeForce RTX 3090 cards with 8 GB of memory and Intel Core CPU with 256 GB RAM to train NDM-net. Calculations were performed using the Pytorch framework.

3 Dataset Construction Options

3.1 Equally Distributed Sources

This type of sample is formed quite simply: equidistant sources are taken in accordance with the formula:

$$J_d = 1, k, 2k, ..., q(k)k,$$

where $l \in \mathbf{N}, k > 1$ and $q(k) = N^s/k$. Determine the distance between the sources:

$$d_d = \sqrt{\sum_{k=1}^{3} (\vec{r}_k^i - \vec{r}_k^j)^2},$$

where $\vec{r} = (x_s, y_s, z_s)$ is the source position.

3.2 Dataset Based on the Seismograms Difference

Another approach to the construction of training sample is the use of metrics in the space of seismograms on the base of L_2 norm:

$$d_s^{ij} = 2\frac{\|\vec{u}(t, \vec{r}_o, \vec{r}_s^j) - \vec{u}(t, \vec{r}_o, \vec{r}_s^i)\|_2}{\|\vec{u}(t, \vec{r}_o, \vec{r}_s^j)\|_2 + \|\vec{u}(t, \vec{r}_o, \vec{r}_s^i)\|_2}, \tag{2}$$

where

$$\|\vec{u}(t, \vec{r}_o, \vec{r}_s^i)\|_2^2 = \sum_{n=1}^{N_t} \sum_{m=1}^{N_o} [(u_1(t_n, x_o^m, x_s^i))^2 + (u_2(t_n, x_o^m, x_s^i))^2 + (u_3(t_n, x_o^m, x_s^j))^2], \tag{3}$$

where N_t is the number of samples in time, N_o number of traces in the seismogramm.

3.3 Dataset Based on the Velocity Models Discrepancy

We introduce a metric in the space of velocity models, which represent a subdomains of the model centered over the source positions that are used to simulate seismic fields. Thus, let $M(\vec{r}, \vec{r}_s^{\,j}) \subset M(\vec{r})$, where $M(\vec{r})$ is the entire velocity model.

The distance between $M(\vec{r}, \vec{r}_s^{\,i})$ and $M(\vec{r}, \vec{r}_s^{\,j})$ is

$$d_m^{ij} = 2\frac{\|M(\vec{r}, \vec{r}_s^{\,j}) - M(\vec{r}, \vec{r}_s^{\,i})\|_2}{\|M(\vec{r}, \vec{r}_s^{\,j})\|_2 + \|M(\vec{r}, \vec{r}_s^{\,i})\|_2}, \tag{4}$$

where

$$\|M(\vec{r}, \vec{r}_s^{\,i})\|_2^2 = \int_0^Z \int_{\vec{r}_s^{\,i}-L_x}^{\vec{r}_s^{\,i}+L_x} \left[v_p^2(\vec{r}) + v_s^2(\vec{r})\right] dxdz.$$

We focused on p-wave velocity v_p and shear-wave velocity v_s as the model parameters, which depend on the Lame parameters as $v_p = \sqrt{\frac{\lambda+2\mu}{\rho}}$ and $v_s = \sqrt{\frac{\mu}{\rho}}$.

3.4 Clustering Analysis and Hausdorff Metric

Since we can pre-calculate the distance matrices corresponding to the three metrics introduced, we can perform a cluster analysis to form a representative sample. Thus, in this work we use density-based clustering hierarchy (HDBSCAN) [2]. This algorithm was chosen due to its speed of calculations, and can also reveal the properties of the entire data set with clusters of different densities.

The algorithm determines the distance of mutual reachability - a new metric of distance between data to separate low-density data:

$$d_{\mathrm{mreach}-k}(a, b) = \max\{\mathrm{core}_k(a), \mathrm{core}_k(b), d(a, b)\},$$

where $\mathrm{core}_k(a)$ is the core distance for k-th nearest neighbor for a point a, $d(a, b)$ is the initial metric distance between the a and b. This metric allows you to leave high-density data at the same distance from each other, and lower-density data is moved away.

To conduct statistical analysis, which we will describe later, we use the Hausdorff metric between the training sample and the entire dataset. The Hausdorff metric calculates the maximum possible distance from each point of one set to the nearest point of the second set.

The Hausdorff distance between two sets for three entered distances d_d, d_s, d_m can be defined as

$$\begin{aligned}
\delta_d &= \max_{\vec{r}_s^{\,i} \in S} \min_{\vec{r}_s^{\,j} \in S_0} d_d^{ij}(\vec{r}_s^{\,j}, \vec{r}_s^{\,i}), \\
\delta_s &= \max_{\vec{u}^{\,i} \in S} \min_{\vec{u}^{\,j} \in S_0} d_s^{ij}(\vec{u}(t, \vec{r}_o, \vec{r}_s^{\,j}), \vec{u}(t, \vec{r}_o, \vec{r}_s^{\,j})), \\
\delta_m &= \max_{M^i \in S} \min_{M^j \in S_0} d_m^{ij}(M(\vec{r}, \vec{r}_s^{\,j}), M(\vec{r}, \vec{r}_s^{\,j})).
\end{aligned} \tag{5}$$

3.5 Statistical Analysis for Fixed N

In this section, we provide global sensitivity analysis [27,28] to estimate the effect of each distances on the error between seismograms with reduced numerical dispersion and clear seismograms and find out which metric to take so that the error is minimal.

Global Sensitivity Analysis. We generated random training datasets and trained NDM-net on each of them. Next, we apply this network to the entire set of seismograms modeled on a coarse grid and calculated the average error:

$$\tilde{\varepsilon} = \frac{1}{N^s} \sum_{i=1}^{N^s} d_s \left(G \left[\vec{u}_{h_2}(t, \vec{r}_o, \vec{r}_i^s) \right], \vec{u}_{h_1}(t, \vec{r}_o, \vec{r}_i^s) \right).$$

Note, that for each randomly generated dataset S_t we can estimate four parameters: size of dataset $N = dim\{S_t\}$ and three Hausdorff distances $\delta_d, \delta_s, \delta_m$. Thus, we can investigate a model in the form of $\tilde{\varepsilon}(\vec{y})$, where $\vec{y} = (N, \delta_d, \delta_s, \delta_m)^T \in [0,1]^4$ with using of sensitivity analysis. We use the Sobol $S_i \in [0,1]$ indices at the first order

$$S_i = \frac{Var(\mathbf{E}_{\vec{y} \sim i}(\tilde{\varepsilon}|y_i))}{Var(\tilde{\varepsilon})}, \quad \sum_i S_i = 1$$

where $\mathbf{E}$ is the mathematical expectation, and Var is variance, y_i is the $i-$th parameter, $\vec{y} \sim i$ is the set of all parameters but y_i. Sobol indices at the first order illustrate how input parameter y_i impact on the output.

Statistical Analysis. It is clear that the other three parameters also strongly depend on the sample size. But in order to conduct a global sensitive analysis, the model parameter must be uncorrelated. And therefore, it is reasonable to reformulate the problem in such a way that for fixed N we consider the error as

$$\tilde{\varepsilon}_{N_c}(\delta_1, \delta_2, \delta_3) = \tilde{\varepsilon}_0 + \alpha_1 \delta_1 + \alpha_2 \delta_2 + \alpha_3 \delta_3 + o(\delta_1, \delta_2, \delta_3),$$

where $\tilde{\varepsilon}_{N_c}$ is the error for fixed size of sample $N_c = const$, $(\delta_1, \delta_2, \delta_3) = (\delta_d, \delta_s, \delta_m)$. It is clear that minimization of the error is equivalent to the minimization of the linear combination

$$l(\delta_1, \delta_2, \delta_3) = q(\alpha_1 \delta_1 + \alpha_2 \delta_2 + \alpha_3 \delta_3) \to \min,$$

where q is any positive real number.

The Sobol coefficients for linear function will be exactly equal to the following expression:

$$S_{\delta_i} = \frac{Var(\mathbf{E}_{\vec{\delta} \sim i}(\tilde{\varepsilon}|\delta_i))}{Var(\tilde{\varepsilon})} = \frac{(\alpha_i L_{\delta_i})^2}{\sum_j (\alpha_j L_{\delta_j})^2},$$

where L_{δ_i} is the extent of δ_i. We can calculate the α_1, α_2 and α_3 using regression analysis and then normalized and averaged for the new metric as follows:

$$\widetilde{\alpha_i} = \frac{1}{N_r} \sum_{k=0}^{N_r} \frac{\sqrt{S_i^k \sum_j (\alpha_j^k L_j^k)^2}}{L_i^k}$$

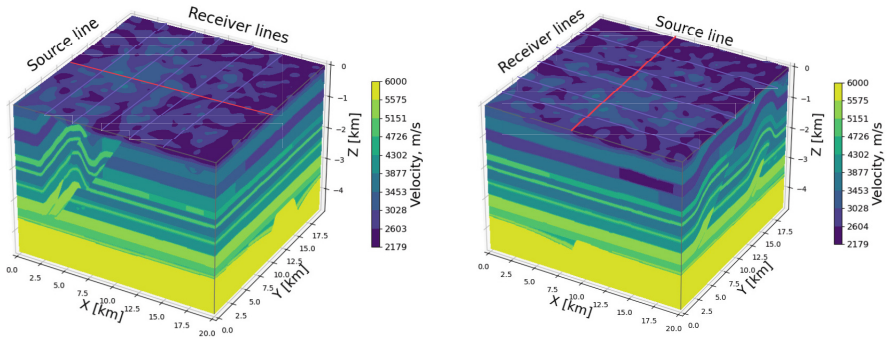
where N_r is the number of random training datasets.

4 Numerical Experiments

4.1 Input Data

To conduct numerical experiments, the Overthrust model [1] was used as a synthetic three-dimensional model, which has a fault, a salt level in the base and a layered structure. The size of the model is $20025 \times 20025 \times 4675$ m^3. We use an acquisition system that simulates 3D modeling, that is, the receiver lines are orthogonal to the source lines, as shown in Figs. 2a and b. The receiver lines are located at a distance of 20 m from each other, while the source lines are located at a distance of 100 m from each other. The number of sources in one line is 1001. The number of receiver for each sources is 513. In total, we have 401401 sources for dataset.

We calculate seismograms with steps of 5 and 2.5 m up to 5 s, with a time step of 2 ms. The central frequency of the wavelet Ricker is 30 Hz.



(a) (b)

Fig. 2. The 3D Oberthrust velocity model (V_p). The red line represents source line position. The blue lines indicate the positions of the receiver lines. We will call such a acquisition system as s: a) crossline; b) inline. (Color figure online)

4.2 Distance Matrices

An important part of our analysis is the construction of distance matrices for each of the metrics. We store the matrices in block form, each block is the distance between the data from the observation lines. Thus, Fig. 3 shows a matrix of distances between the positions of the sources, two blocks are highlighted, which correspond to the distance between the sources $((x_1)_i, 0, 0)_{i=1}^{N^s}$ and $((x_1)_i, 0, 0)_{i=1}^{N^s}$, as well as $((x_1)_i, 0, 0)_{i=1}^{N^s}$ and $((x_1)_i, 20020, 0)_{i=1}^{N^s}$. Figure 4 shows the distance matrix between seismograms in the same format and Fig. 5 shows the distance matrix between velocity models.

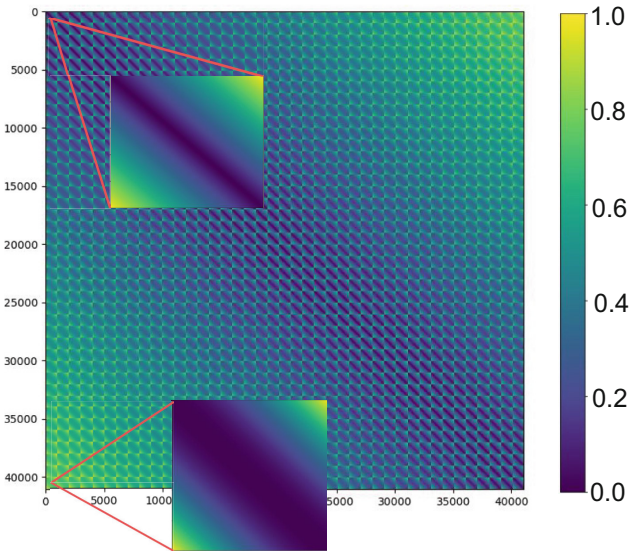


Fig. 3. Distance Matrix based on Euclidian distance between the source position

The difference between the data is small where the values of the distance matrices are small (blue area). Each of the matrices conveys the properties of each data type, thus we can use them to build a representative sample using cluster analysis and reflect the properties of the data in them.

4.3 Training Experiments and Results

This section presents the statistical analysis results for two models, as well as a comparison of the training NDM-net on the training datasets constructed by a different methods.

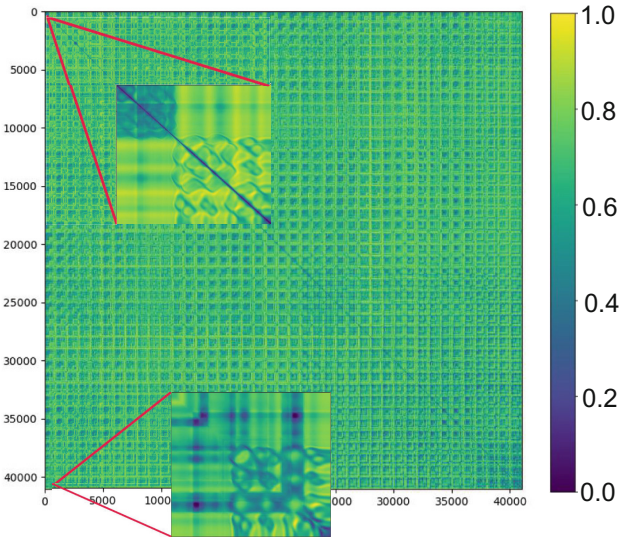


Fig. 4. Distance Matrix based on distance between the seismograms

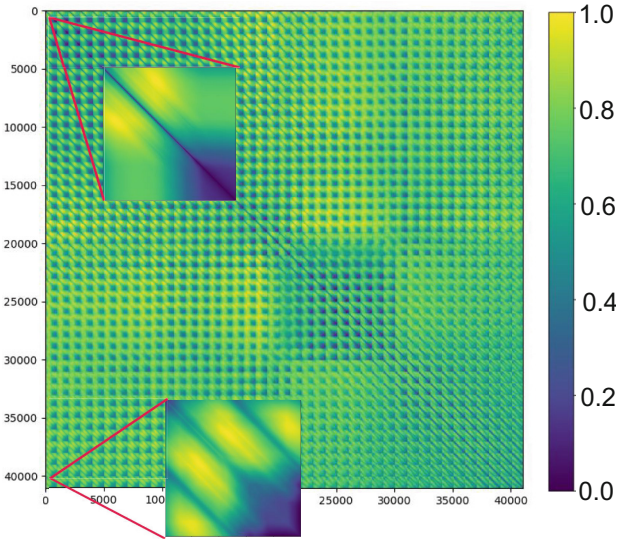


Fig. 5. Distance Matrix based on distance between the Velocity models

Statistical Analysis Results. The Table 1 shows the results of implementing global sensitivity analysis, and the coefficients of the linear part of the error function. Note, that the Sobol indices and the decomposition coefficients have approximately the same values for both models. This allow us to assert a certain universality of estimates.

Table 1. Global Sensitivity Analysis Results

S_{δ_d}	S_{δ_s}	S_{δ_m}	$\widetilde{\alpha}_d$	$\widetilde{\alpha}_s$	$\widetilde{\alpha}_m$
0.46	0.325	0.22	0.37	0.33	0.3

Thus, we can introduce a new metric as a combination of three distances

$$0.37\delta_d + 0.33\delta_s + 0.3\delta_m \to \min . \tag{6}$$

Numerical Experiments. We consider four types of training dataset: $D^{H_d}, D^{H_s}, D^{H_m}$ and $D^{H_{new}}$ build on the basis of the introduced metrics (5) and a combine metric (6) respectively, and train on them NDM-net to compare the results.

We also use the relative error between the postprocessing result and the fine-grid solution to verify the approach:

$$\tilde{\varepsilon}_{rel} = \frac{1}{N_r} \sum_{i=1}^{N_r} \frac{||(G\,[\vec{u}_{h_2}(t, \vec{r}_o, \vec{r}_i^{\,s})] - \vec{u}_{h_1}(t, \vec{r}_o, \vec{r}_i^{\,s})||_2}{||\vec{u}_{h_1}(t, \vec{r}_o, \vec{r}_i^{\,s})||_2},$$

where N_r- is the random distributed indexes of sources. The distribution of sources that are included in the training sample is shown in Fig. 6, as well as the

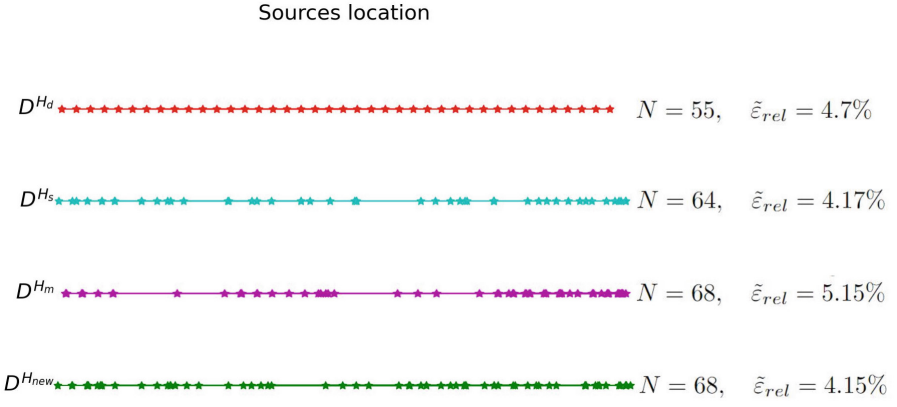


Fig. 6. Distribution of the source positions, which includes in training sample

average error corresponding to the samples. The initial relative error is $\tilde{\varepsilon}_{rel} = 14.8\%$.

We provided the mean errors $\tilde{\varepsilon}$ between the generated seismograms of a trained neural network $\{G(\vec{u}_{h_2})\}_{i=1}^{N^s}$ and accurate seismograms $\{\vec{u}_{h_1}\}_{i=1}^{N^s}$, depending on the size of the training sample N for different training datasets and for both velocity models (Fig. 7). Also, an error is shown for randomly generated training samples (gray dots) to show the positions of the training results using various training datasets. It can be noticed that the optimized dataset is relatively lower than all other datasets in terms of error values.

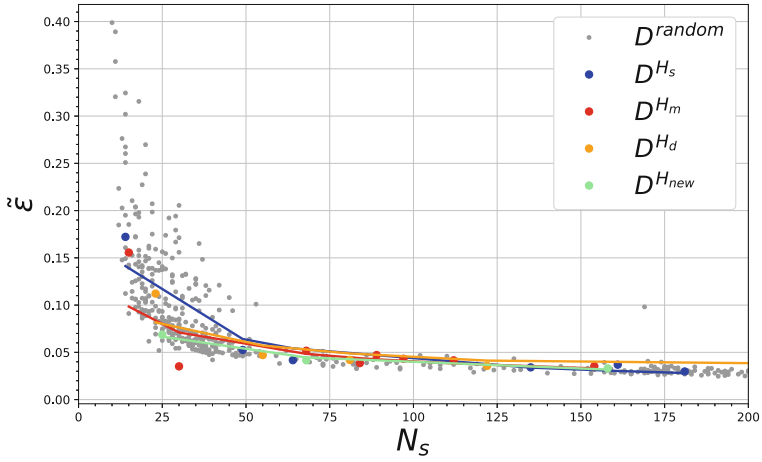


Fig. 7. The average error of applying NDM-net to all data, depending on the size of training dataset for different types of samples for BP model

It is worth noting that the initial average error was 0.15, which allows us to say that using the presented method, the numerical dispersion can be suppressed 3 times for metric $\tilde{\varepsilon}$ in the three-dimensional case, even with a relatively small number of sources in the training sample (0.014% of the number sources in the surveillance system) and 6.25 times for the sample size of 0.08% of the total number of sources.

5 Conclusion

In this study, we developed a method to mitigate numerical dispersion in seismic data using 3D acquisition system, focusing on the construction of the representative sample. The proposed method includes the calculation of the distance matrix using three different metrics that reflect the properties of the data and cluster analysis. We conducted numerical experiments on synthetic data and showed that all construction techniques generalize well to the three-dimensional case. The proposed method makes it possible to suppress the numerical variance from the initial average value of 14.8% up to 2.35% for training size of 0.08%.

References

1. Aminzadeh, F., Brac, J., Kunz, T.: SEG/EAGE 3-D salt and overthrust models. SEG/EAGE 3-D Modeling Series, No. 1: Distribution CD of Salt and Overthrust models. SEG Book Series (1997)
2. Campello, R.J.G.B., Moulavi, D., Sander, J.: Density-based clustering based on hierarchical density estimates. In: Pei, J., Tseng, V.S., Cao, L., Motoda, H., Xu, G. (eds.) PAKDD 2013. LNCS (LNAI), vol. 7819, pp. 160–172. Springer, Heidelberg (2013). https://doi.org/10.1007/978-3-642-37456-2_14
3. Chen, J.B.: A 27-point scheme for a 3D frequency-domain scalar wave equation based on an average-derivative method. Geophys. Prospect. **62**(2), 258–277 (2014)
4. Gadylshin, K., Lisitsa, V., Gadylshina, K., Vishnevsky, D.: Optimization of the training dataset for numerical dispersion mitigation neural network. In: Gervasi, O., Murgante, B., Misra, S., Rocha, A.M.A.C., Garau, C. (eds.) Computational Science and Its Applications, ICCSA 2022 Workshops, vol. 13378, pp. 295–309. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-10562-3_22
5. Gadylshin, K., Lisitsa, V., Vishnevsky, D., Gadylshina, K.: Hausdorff-distance-based training dataset construction for numerical dispersion mitigation neural network. Comput. Geosci. **180**, 105438 (2023). https://doi.org/10.1016/j.cageo.2023.105438
6. Gadylshin, K., Vishnevsky, D., Gadylshina, K., Lisitsa, V.: Numerical dispersion mitigation neural network for seismic modeling. Geophysics **87**(3), T237–T249 (2022)
7. Gondyul, E., Lisitsa, V., Gadylshin, K., Vishnevsky, D.: Numerical dispersion mitigation neural network with the model-based training dataset optimization. In: Gervasi, O., Murgante, B., Rocha, A.M.A.C., Garau, C., Scorza, F., Karaca, Y., Torre, C.M. (eds.) Computational Science and Its Applications, ICCSA 2023 Workshops. LNCS, vol. 14106, pp. 19–30. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-37111-0_2
8. Goodfellow, I.J., et al.: Generative adversarial networks (2014)
9. Jia, F., Wong, W.H., Zeng, T.: DDUNet: dense dense U-Net with applications in image denoising. In: Proceedings of the IEEE/CVF International Conference on Computer Vision (ICCV) Workshops, pp. 354–364, October 2021
10. Kaser, M., Dumbser, M., Puente, J., Igel, H.: An arbitrary high-order Discontinuous Galerkin method for elastic waves on unstructured meshes iii. viscoelastic attenuation. Geophys. J. Int. **168**(1), 224–242 (2007). https://doi.org/10.1111/j.1365-246X.2006.03193.x
11. Kaur, H., Fomel, S., Pham, N.: Seismic ground-roll noise attenuation using deep learning. Geophys. Prospect. **68**(7), 2064–2077 (2020)
12. Koene, E., Robertsson, J.: Removing numerical dispersion artifacts from reverse time migration and full-waveform inversion, pp. 4143–4147 (2017)
13. Kostin, V., Lisitsa, V., Reshetova, G., Tcheverda, V.: Local time-space mesh refinement for simulation of elastic wave propagation in multi-scale media. J. Comput. Phys. **281**, 669–689 (2015)
14. Levander, A.: Fourth-order finite-difference P-S. Geophysics **53**, 1425–1436 (1988). https://doi.org/10.1190/1.1442422
15. Li, Y., Ku, B., Zhang, S., Ahn, J.K., ko, H.: Seismic data augmentation based on conditional generative adversarial networks. Sensors **20**, 6850 (2020). https://doi.org/10.3390/s20236850

16. Lisitsa, V.: Dispersion analysis of Discontinuous Galerkin method on triangular mesh for elastic wave equation. Appl. Math. Model. **40**, 5077–5095 (2016). https://doi.org/10.1016/j.apm.2015.12.039
17. Liu, Y.: Optimal staggered-grid finite-difference schemes based on least-squares for wave equation modelling. Geophys. J. Int. **197**(2), 1033–1047 (2014)
18. Liu, Y., Sen, M.K.: A new time-space domain high-order finite-difference method for the acoustic wave equation. J. Comput. Phys. **228**(23), 8779–8806 (2009)
19. Mittet, R.: Second-order time integration of the wave equation with dispersion correction procedures. Geophysics **84**(4), T221–T235 (2019)
20. Mulder, W.A.: Temporal dispersion correction for wave-propagation modelling with a series approach. Geophys. Prospect. **72**, 301–314 (2023). https://doi.org/10.1111/1365-2478.13411
21. Oliveira, D., Ferreira, R., Silva, R., Brazil, E.V.: Interpolating seismic data with conditional generative adversarial networks. IEEE Geosci. Remote Sens. Lett. **15**(12), 1952–1956 (2018)
22. O'Reilly, O., Lundquist, T., Dunham, E.M., Nordstrom, J.: Energy stable and high-order-accurate finite difference methods on staggered grids. J. Comput. Phys. **346**, 572–589 (2017). https://doi.org/10.1016/j.jcp.2017.06.030
23. Park, J., Choi, J., Jee Seol, S., Byun, J., Kim, Y.: A method for adequate selection of training data sets to reconstruct seismic data using a convolutional U-Net. Geophysics **86**, V375–V388 (2021)
24. Pleshkevich, A., Vishnevskiy, D., Lisitsa, V.: Sixth-order accurate pseudo-spectral method for solving one-way wave equation. Appl. Math. Comput. **359**, 34–51 (2019)
25. Pleshkevich, A., Vishnevsky, D., Lisitsa, V., Levchenko, V.: Parallel algorithm for one-way wave equation based migration for seismic imaging. In: Voevodin, V., Sobolev, S. (eds.) RuSCDays 2018. CCIS, vol. 965, pp. 125–135. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-05807-4_11
26. Ronneberger, O., Fischer, P., Brox, T.: U-Net: convolutional networks for biomedical image segmentation. In: Navab, N., Hornegger, J., Wells, W.M., Frangi, A.F. (eds.) MICCAI 2015. LNCS, vol. 9351, pp. 234–241. Springer, Cham (2015). https://doi.org/10.1007/978-3-319-24574-4_28
27. Saltelli, A.: Global sensitivity analysis: an introduction. In: Proceedings of the 4th International Conference on Sensitivity Analysis of Model Output, SAMO 2004, January 2004
28. Sobol', I.M.: Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. Math. Comput. Simul. **55**(1), 271–280 (2001). https://doi.org/10.1016/S0378-4754(00)00270-6
29. Tan, S., Huang, L.: A staggered-grid finite-difference scheme optimized in the time-space domain for modeling scalar-wave propagation. In: SEG Technical Program Expanded Abstracts 2014, pp. 3292–3296 (2014)
30. Virieux, J.: P-SV wave propagation in heterogeneous media: Velocity-stress finite-difference method. Geophysics **51**(4), 889–901 (1986)
31. Virieux, J., Calandra, H., Plessix, R.E.: A review of the spectral, pseudo-spectral, finite-difference and finite-element modelling techniques for geophysical imaging. Geophys. Prospect. **59**(5), 794–813 (2011). https://doi.org/10.1111/j.1365-2478.2011.00967.x
32. Virieux, J., et al.: Seismic wave modeling for seismic imaging. Lead. Edge **28**(5), 538–544 (2009)

33. Wang, R., Meng, Y., Zhang, W., Li, Z., Hu, F., Meng, L.: Remote sensing semantic segregation for water information extraction: optimization of samples via training error performance. IEEE Access **7**, 13383–13395 (2019). https://doi.org/10.1109/ACCESS.2019.2894099
34. Yan, S., Zhang, L., Liu, D.: An empirical study on optimization of training dataset in harmfulness prediction of code clone using ensemble feature selection model. In: 2018 5th International Conference on Information and Communication Technologies for Disaster Management, December 2018, pp. 1–4 (2018). https://doi.org/10.1109/ICT-DM.2018.8636375
35. Yu, S., Ma, J., Wang, W.: Deep learning for denoising. Geophysics **84**, 1–107 (2019)

Sustainable Digital Circular Economy (DiCE 2024)

Integrating Territorialization, Circular Economy, and Industrial Symbiosis: Leveraging GIS for Enhanced Efficiency in Industrial Zones

Francesca Sinatra[1(✉)], Giuseppe Borruso[1], and Sandra Primiceri[2]

[1] DEAMS - Department of Economics, Business, Mathematics and Statistics "Bruno de Finetti", University of Trieste, Via A.Valerio 4/1, 34127 Trieste, Italy
francesca.sinatra@phd.units.it, giuseppe.borruso@deams.units.it
[2] Consorzio di Sviluppo Locale dell'Area Giuliana, Via G. e S. Caboto 14, 34147 Trieste, Italy
sandra.primiceri@coselag.it

Abstract. Territorialization, Circular Economy and Industrial Symbiosis represent key concepts in the context of industrial areas. Present days industrial settings and plans are characterized by a growing attention towards sustainable development, and the processes of territorialization are more and more meant to address a responsible use of natural resources and territory planning in order to maximize efficiency and reduce environmental impact. This challenge involves creating a connection where industrial areas develop clusters, with interconnected business establishing proximity to leverage synergies, share resources, and expertise. Industrial symbiosis and circularity can be facilitated by clusters, which can contribute to sustainability. The purpose of this study is to address circular economy and industrial symbiosis in a spatial analytical framework, proposing a combined methodology of addressing the spatial organization of industrial areas to promote circular activities. A traditional locational analysis method is adapted to circularity and, in this framework, different steps were proposed, involving the use of Geographical Information System (GIS) in the visualization and analysis of an industrial area, with a particular focus on a case study of the industrial area in Trieste. The GIS method enables the mapping of resources, infrastructure, and potential synergies among businesses. The implementation of a geographical database for an initial visual analysis can be a first support to stakeholders in identifying opportunities for cooperation, resource sharing, and optimization of synergy. By adopting this methodology, economic sustainability is not only promoted but also environmental impact is minimized, and a resilient industrial community is established. The importance of this paper lies in highlighting how the GIS approach can help support circular economy policies by providing a foundation for sustainable planning and management of industrial areas.

Keywords: GIS · Industrial Symbiosis · Territorialization · Circular Economy

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 369–383, 2024.
https://doi.org/10.1007/978-3-031-65238-7_25

1 Introduction

1.1 Circular Economy and Industrial Symbiosis

The Circular Economy (CE) and the Industrial Symbiosis (IS) play a fundamental role in the promotion of new processes of localization and territorialization of productive activities. Through a case study, the present work will try to investigate the effect that the adoption of circular economic models and the implementation of industrial synergies have on the localization of enterprises activities and their subsequent interaction with the territory.

Over the years, different definitions have been developed for the circular economy. In particular, we want to highlight the one provided by the Ellen MacArthur Foundation (2016): "A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles" [1]. This is a closed-loop economy that aims to turn generated waste into new secondary raw materials by reusing it.

On the other hand, the Industrial Symbiosis (IS) is a concept that refers to the integration and collaboration between different companies and sectors, with the aim of optimizing the use of resources, the reduction of waste but also improving the overall efficiency of the production system. In relation to the theoretical framework, this concept will be defined through the analysis of the different theories present in the literature. The integration of these concepts is aimed at establishing a more sustainable production/economic system, with the goal of promoting waste reduction and resource efficiency. The use of circular business models can lead to the creation of eco-industrial parks, for instance. However, industrial symbiosis can face obstacles due to lack of information on material flows or distrust of collaboration between competing companies. Consequently, in the literature it appears as the industrial symbiosis is synergistic in the circular transition.

The CE, through the promotion of the re-use and circulation of secondary raw materials and resources, provides new tools for the evaluation and mapping of certain sites. Taking into account social, economic, and environmental impacts, their identification can be achieved through both CE it and localization models. Analyzing the flow of materials in a given area is crucial for identifying opportunities for recycling and/or reuse. Furthermore, this methodological approach promotes the realization of geospatial representations that highlight the possibilities for the development of a given territory, from CE's perspective [2, 3].

Therefore, the present work will focus on the Industrial Zone of Trieste, thanks to the collaboration carried out with the Co.SELAG (Consortium of Local Economic Development of the Giuliana Area). The latter is a public economic body whose function is to promote and improve the creation and development of productive and entrepreneurial activities but also research and innovation-related services within their area of competence.

The importance of this study lies in providing an in-depth overview of circular economy practices and industrial symbiosis and providing input for policy makers, entrepreneurs and local stakeholders wishing to promote sustainable localization and territorialization processes, by examining the case study of the Consortium's area. The

adoption of a circular approach and the creation of synergies between companies can contribute to a more resilient economy and better resource management, while promoting local development and environmental sustainability.

1.2 Ports Proximity and the Development of Industrial Areas

Ports have always been important nodes for international trade, and their proximity has led to the development of industrial activities due to their access to different markets.

The development has been influenced by a variety of reasons, including access to raw materials and the advantage of reducing transportation costs, which encourages competitive production. Moreover, the proximity of industrial areas to ports has easily allowed the production export around the world, creating new opportunities.

The economic development of several cities has been greatly impacted by the proximity and connection between industry and port due to their efficiency and connections.

Despite modern times, this connection is still evident in a number of cities where ports are still a crucial part of the local economy.

In spite of this, the existing relationship between ports and industrial areas today is still evolving with globalization and relocation of activities there has been a withdrawal of companies from port areas, while, at the same time, the new industries, in particular those tied to logistics and tourism, continue to emerge near ports. In this sense the port and city's functions are mixing, creating hybridized situations where formerly port-related areas are converted to urban functions, while new urbanized spaces, not always proximal to port areas, but also located in inland, are dedicated to transport, logistic and industrial functions [4].

Therefore, the proximity between industrial areas and ports remains a unique feature for urban economic development, leading to increasing synergies within which industrial areas can progress [5–8].

The paper is organized as it follows: Section 2 Theoretical and methodological aspects; Subsection 2.1 Theories of industrial activity localization; Subsection 2.2 The industrial location theory within a circular framework; Section 3 The application of circular economy's principles.; Subsection 3.1 The study area; Subsection 3.2 Case studies: towards circular economy in the Industrial Zone of Trieste Sect. 4 Result and discussion; Subsection 4.1 Industrial Symbiosis in the Industrial Zone of Trieste; Section 4.2 Circular Economy in the Industrial Zone of Trieste; sub-paragraph Sect. 5 Conclusion.

2 Theoretical and Methodological Aspects

The ratio behind the development of the present research work has its roots within a various as well as articulated theoretical, methodological and operational framework, involving different segments to be integrated and exploited. The research work is in particular aimed at setting a framework for an applied research activity hypotezising and planning the implementation of an industrial symbiosis within an industrial area, revisiting a traditional geographical model of industrial location within a circular economy frame.

2.1 Theories of Industrial Activity Localization

The location of industrial activities is a crucial issue in economic studies, affecting the competitiveness and socio-economic development of regions and countries. Economic space is a set of functional and hierarchical relationships that define the division of labor between the different territorial units. These relationships include economic-functional aspects, where actors act rationally to achieve goals, and aspects of domination or contradiction. The objective of territorial economics is to understand and interpret this complex of relationships [9].

Traditional theories have focused mainly on one of two dimensions: the economic-functional or the domination. However, there are cultural and theoretical premises for a synthesis of the two positions.

Two theories that have profoundly contributed to the understanding of this phenomenon are Alfred Weber's theory of industrial localization and Johann Heinrich von Thünen's model of the spatial distribution of agricultural activities [10].

Weber, in the early 20th century, formulated a theory based on the optimization of production costs. He identified three key factors in the location decision: proximity to raw materials, proximity to consumer markets and accessibility to transport. Companies, according to Weber, try to minimize costs by moving to places that offer an optimal balance between these factors (Fig. 1B). This theory stressed the strategic importance of location decisions in the context of industrial competitiveness [11].

The von Thünen model, developed in the nineteenth century, was originally focused on agriculture, but its concept of concentricity of activities based on transport costs influenced the future understanding of industrial localizations. Von Thünen proposed that agricultural activities should be organized concentrically around an urban center, based on transport costs and land profitability (Fig. 1A). This concept of spatial distribution of activities has stimulated further reflection on the influence of transport costs in economic location [12].

Both models address the issue of economic localization in a complementary way. While Weber focuses on production costs and logistics, von Thünen introduces the concept of distance from the center as a key element in the location decision.

Integrating these approaches could provide a more comprehensive view of the spatial dynamics of economic activities, considering both industrial and agricultural aspects.

The theories of Weber and von Thünen provided essential conceptual foundations for understanding the strategies of localization of industrial activities. The integrated analysis of these models can enrich the understanding of spatial dynamics of economic activities, helping to develop more effective and sustainable industrial policies.

Classical theories of localization and applied economic geography have studied industrial localization primarily in static terms, emphasizing transportation costs and differential economic characteristics of geographical areas.

These approaches consider space as an exogenous data and enterprises adapt to its characteristics. The analysis of spatial domination has focused on power relations at the international, interregional and intraregional levels, often in a Marxian context. A theoretical synthesis is necessary, integrating micro and macro spatial approaches and overcoming the static conception of space. The next sections will examine three lines of

thought: localization economics, localization policy analysis, and localization political economics.

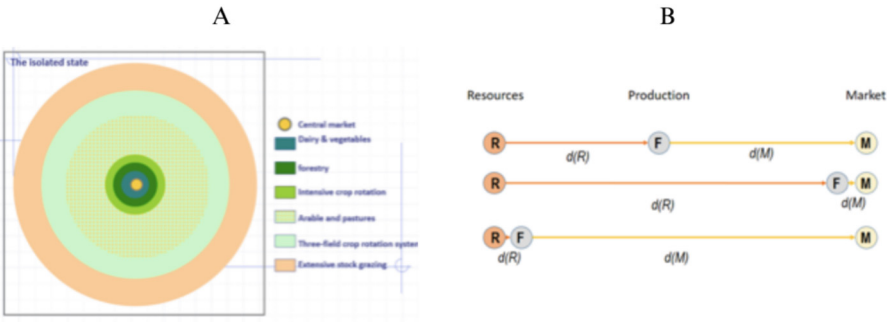


Fig. 1. A: Von Thünen's model of land use. Source: Von Thünen J.H. (1826) [12] B: Location à la Weber in the simplified model (along a line). Source: Balletto et al. (2019) after Weber (1909).

2.2 The Industrial Location Theory Within a Circular Framework

An extension of the classical Weber's model of industrial location can be to-date adapted to host circularity, as studied and applied to the case of construction and demolition waste in the MEISAR project [14]. The idea is that of minimizing transport costs related to materials, energy and products extended to recycled waste in the twofold nature of waste and potential secondary raw materials. This implies a change of paradigm, as the place of production, whose location is central in the original Weber's theory, becomes also a place of origin of second raw materials. The same production plant can be de facto localized in close proximity to the places of production of waste. Furthermore, waste processing plants - in their journey towards becoming secondary raw materials - can be the object of location choices and minimization of costs, by the consideration of the 'to & fro' waste-materials' transport costs (Fig. 2). It is therefore needed a high level of flexibility in realizing mobile plants. The traditional non-circular location model needs to be reconsidered in order to correctly quantify the quantity of waste produced and its percentage of reinsertion into a circular - symbiotical - production process. An estimation of the overall production costs need therefore to be performed, where externalities of production, waste production and reuse can be estimated. In this sense, the modified model could be interesting for both considering new locations for processing waste, and also for favouring rise of new business given the proximity of the different activities.

A consequence of that is the need to correctly and precisely map the potential actors involved in the process. This requires a deep work of data organization and harmonization, also by means of geographical analytical and sharing tools (GIS software and geographical sharing packages).

A consequence of that is the need to correctly and precisely map the potential actors involved in the process. This requires a deep work of data organization and harmonization, also by means of geographical analytical and sharing tools (GIS software and geographical sharing packages).

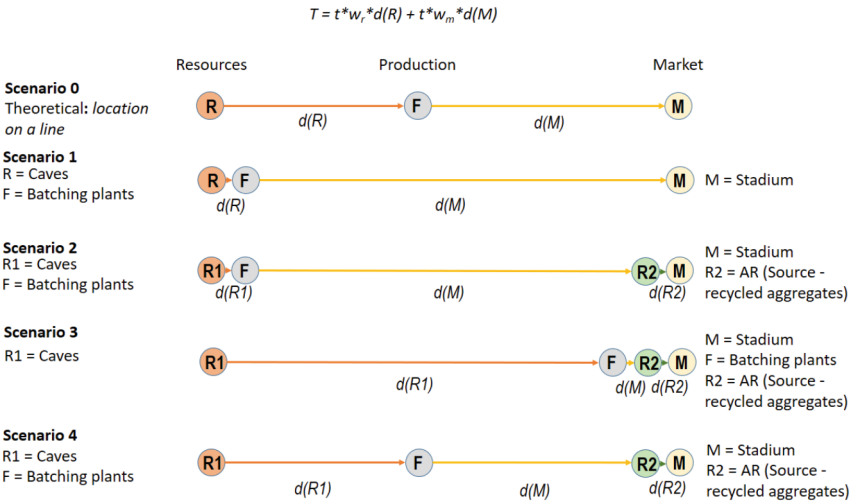


Fig. 2. The Weberian localization model of batching plants in a circular economy: case study of a stadium demolition and demolition. Source: Balletto et al. (2019) [13]

3 The Application of Circular Economy's Principles

An application is proposed, considering a case study based on the industrial area of Trieste (Italy). The idea is that of taking into the consideration the industrial activities based in this area proposing possible applications of circular economy and industrial symbiosis.

3.1 The Study Area

The area under study corresponds to the Industrial Zone of Trieste, specifically the area of competence of Co.SELAG that includes portions of the municipalities of Trieste, Muggia and San Dorligo della Valle. Located in the region of Friuli-Venezia Giulia and consequently in north-eastern Italy, the study area is a strategic point not only for its geographical position but also from an industrial and logistical point of view, given its proximity to the borders of Slovenia, Austria and Croatia and being the port a crucial hub for international trade.

The ultimate goal of the Consortium is to contribute to economic growth and the creation of jobs within its territory, trying to promote the technological development and competitiveness of local businesses [15, 16]. The Consortium has been charged, through the regional law n. 3 of 20 February 2015, to manage the industrial area that was previously under the responsibility of the Agency for the Industrial Zone of Trieste (EZIT). This transition occurred following the liquidation of the EZIT at the end of 2015, definitively concluding the procedure in April 2019.

It is important to underline that the management of the legacy of EZIT represents a great responsibility, with the aim of preserving its memory and continuing to develop the Industrial Area of Trieste. The history of the EZIT dates back to the early post-war period,

when it was established as the "Coordinating Body for the Industrial Development of Zaule".

The Co.SELAG is charged from the Region Friuli Venezia Giulia to conclude the procedure of liquidation of the Agency for the Industrial Zone of Trieste (EZIT) that was in course from 2015. With the conclusion of the procedure of liquidation, this new consortium structure, with a participation of 52% from the Authority of Harbour System and 48% from the municipalities of Trieste, Muggia and San Dorligo of the Valley-Dolina, is now able to resume its activities and attract new entrepreneurial initiatives to revitalize the area.

It is important to note that Co.SELAG plays a strategic role both in terms of logistics and real estate and is also committed to the integration with the waterway and management of FREEeste, the area formerly belonging to Finnish marine technology firm Wärtsilä's production plant, now an inner harbor and free zone part of Trieste Port Authority. In this perspective, the port becomes a key player in the industrial policy of the territory, in which the governance model unites the port itself, logistics and manufacturing.

The strategic position of this industrial area, crossed by important road, highway and railway connections, allows joining the port of Trieste with the European net, making it a fundamental node. Moreover, an important road axis crosses the area, connecting northern Italy to Istria region – part of Slovenia and Croatia - through the Rabuiese border, serving important tourist traffic and regional freight offices.

Companies located in the industrial area of Trieste have faced challenges related to the scarcity of space, but recently there is a growing interest by companies of international importance towards the opportunities offered by this industrial area. These positive signs indicate its potential for growth and continued development.

Co.SELAG focuses on the adoption of CE and IS to address the problems related to environmental sustainability, through the launch of an initiative to revitalize the industrial area of its competence. This is an economic public body which also takes into account existing environmental issues and challenges. In fact, it develops several projects in collaboration with both the FVG Region and the European Union.

The first one "APEA" (Ecologically Equipped Production Areas), a project promoted by individual regional consortiums that aims to apply the principles defined in the circular economy within production areas, in order to obtain data on environmental status and energy consumption [15].

The second one "Eco Industrial Park Network for the Alpine Regions Leveraging smart and Circular Economy" (ECOLE) represents the second project which is implemented to try to find a solution to the problems faced by industrial parks in be-coming integrated circular eco-industrial (EIP).

In collaboration with the Regional Administration FVG and the agency ARPA FVG, APEA is designed as an undefined industrial area, consisting of at least two companies with different production vocations, as industry, crafts, trade and agriculture. Characterized by an integrated management of infrastructure and resources, APEA aims to optimize the organization of activities to reduce environmental impact. The primary objective of the APEA project is to improve environmental, industrial and social performance, in line with EU directives, promoting sustainable environmental economic

development and implementing a management model that increases the competitiveness of the companies involved.

On the other hand, the ECOLE project represents a key action aimed at spreading and promoting sustainable development within Industrial Parks. The importance lies in the fact that the project suggests and provides guidelines and a structure to be followed in order to establish Eco-Industrial Parks contributing to the creation of more resilient and sustainable industrial areas [16].

This poses a challenge as it mainly affects industries and also infrastructure providers, industry agencies, business support organizations and public authorities. Since Industrial Parks today have a negative image as polluters and a lack of CE implementation in their value chain and daily activities, cooperation is essential to accelerate this transition, and this is what is proposed within the use of a community approach by establishing an action plan for the implementation of the tools collected in the pilot sites. The project aims to transform industrial parks into more circular, resilient and sustainable EIP in the Alps, able to deal with climate and economic crises [17].

More in depth, the development of this project in the Industrial Zone of Trieste, concerns the realization of a platform which will have the purpose of monitoring energy, water, soil, and waste (etc.) consumption in order to implement and promote strategies of IS.

The two projects have in common the imposition of constraints and objectives aimed at:

- Reduction of environmental impact: involves reducing emissions and waste generated by the same industrial activities through, for example, air monitoring to ensure compliance with environmental standards or the adoption of low carbon technologies.
- Waste management: The projects call, in the case of waste, for improved waste management through separate collection and recycling within the area under consideration. It also seeks to limit the generation of hazardous waste and to encourage responsible waste management.
- Energy efficiency: The objective is to reduce energy consumption through the adoption of specific measures. Incentives for the use of renewable energy sources, the promotion of cogeneration and heat recovery are crucial to improving the overall energy efficiency of the industrial park.

3.2 Towards Circular Economy in the Industrial Zone of Trieste

As part of this study, the data used was provided by the Consortium itself, which allowed the data to be processed in aggregate form. Indeed, within the Co.SELAG a geographical database process implementation has been started, in order to prepare a cognitive tool regarding the real company assets. Localization can provide a "spatial" idea of their location and spatial distribution.

The data provided concerns the companies that are part of the study area, which have been provided in the form of an excel file containing the following information: name, address, contacts, sector type and ATECO code, type of activity established, the size of the company and finally the number of employees.

In the future, the database can be extended with the inclusion of additional company information and data, not only to implement projects to reduce environmental impacts and implement the logic of circularity.

In order to conduce a more in-depth analysis of the study area, the excel file was analyzed. The analysis started from the number of companies present in the industrial area which amounted to 895. Since the main objective of the paper is to understand what the synergies within the study area could be, it was decided to carry out an even more targeted analysis using a series of filters available within the excel file.



Fig. 3. Included sectors in the analysis. Author: Sinatra F. (2024)

As a first filter, it was analysed the column called "Sector 1" within which the macro-areas of belonging companies were taken into account, as we note in Fig. 3 there were 13 different sectors.

In the analysis, have been excluded sectors as the wholesale, retail trade, transport and logistics, gaining a sample of 382 companies. Subsequently, it was applied a second filter regarding the "Business Size" excluding only micro enterprises, obtaining a sample of companies equal to 243.

Since the cells which do not contain any information about the companies' sector were also considered, the corresponding 98 companies were analyzed trying to understand what their activities could be. The ATECO code, allowed to identify it. Infact, ATECO code constitutes in fact a type of classification of economic activities at national level. As a matter of fact, it is an alpha-numerical combination that defines the main activity carried out by the company and which is conferred at the time of enrollment in the Register of Companies [18].

Consequently, companies which could potentially be involved in the creation and/or implementation of circular strategies and industrial symbiosis were 146 companies.

Subsequently, a detailed analysis of the identified companies was carried out excluding the small ones which did not have a very large production, obtaining a final sample of 101 enterprises (including companies that own multiple production facilities).

On the practical side My Maps was used, which is an application that allows the development of an interactive mapping, in order to organize and obtain a geospatial representation of data. This tool was functional for data collection and also for their analysis through the QGIS software [19].

4 Result and Discussion

The Industrial Area of Trieste represents a meaningful example of how its strategic geographic position, combined with a series of logistic, economic, and structural factors, can favor its increase and development.

The map provided gives a clear overview of the locations of the companies and their surroundings, allowing a better understanding of the arrangement of industrial activities. This is essential to identify potential synergies between companies, encouraging collaboration and maximising the use of shared resources.

Moreover, the use of Geographic Information System (GIS) mapping systems is a valuable tool for evaluating access to markets, resources and infrastructure. This approach can significantly contribute to the sustainable planning of the industrial area of Trieste, allowing an optimal management of resources and an intelligent design of infrastructure. The present study has therefore tried to develop a mapping of the aforementioned area through the use of QGIS that emerges as a fundamental geographic informative tool for the analysis of the distribution of the activities carried out within the boundaries of the Consortium (Fig. 4).

The methodological approach used is therefore similar to the one developed in the MEISAR "Materials for Sustainable Construction and Infrastructure: the Recycled Aggregates"- project, based on the core principles of the circular economy. One aspect of this project was the introduction of cluster analysis in which it is essential to take into account the spatial constraint, where the distance between the plants and the place where secondary raw materials are used must not exceed 30 km. The MEISAR Map (Fig. 5) allows the construction of a map that binds to Weber's theory in circular view. [14].

4.1 Industrial Symbiosis in the Industrial Zone

Given the willingness and interest of the Consortium in encouraging sustainable practices in its territory, the latter has carried out a series of interlocutions with its companies in order to evaluate the opportunities for the expansion of production sites.

With reference to the dialogue with one of the companies present in the territory, a need for the use of lemon processing by-products, generated by the processing of liqueurs, has emerged. Until then, the lemons were used exclusively for the outermost part of the skin, while the rest of the product, despite being intact, was no longer used, thus becoming a waste of production for the company.

Consequently, the Consortium has explored the production system of the Industrial Area of Trieste through ad hoc interviews with companies involved in the food sector and which were interested in the waste production of the liquor factory.

After identifying the company that was interested in participating, the team began working together to assess the potential for synergy between the two realities and repeat it in the future.

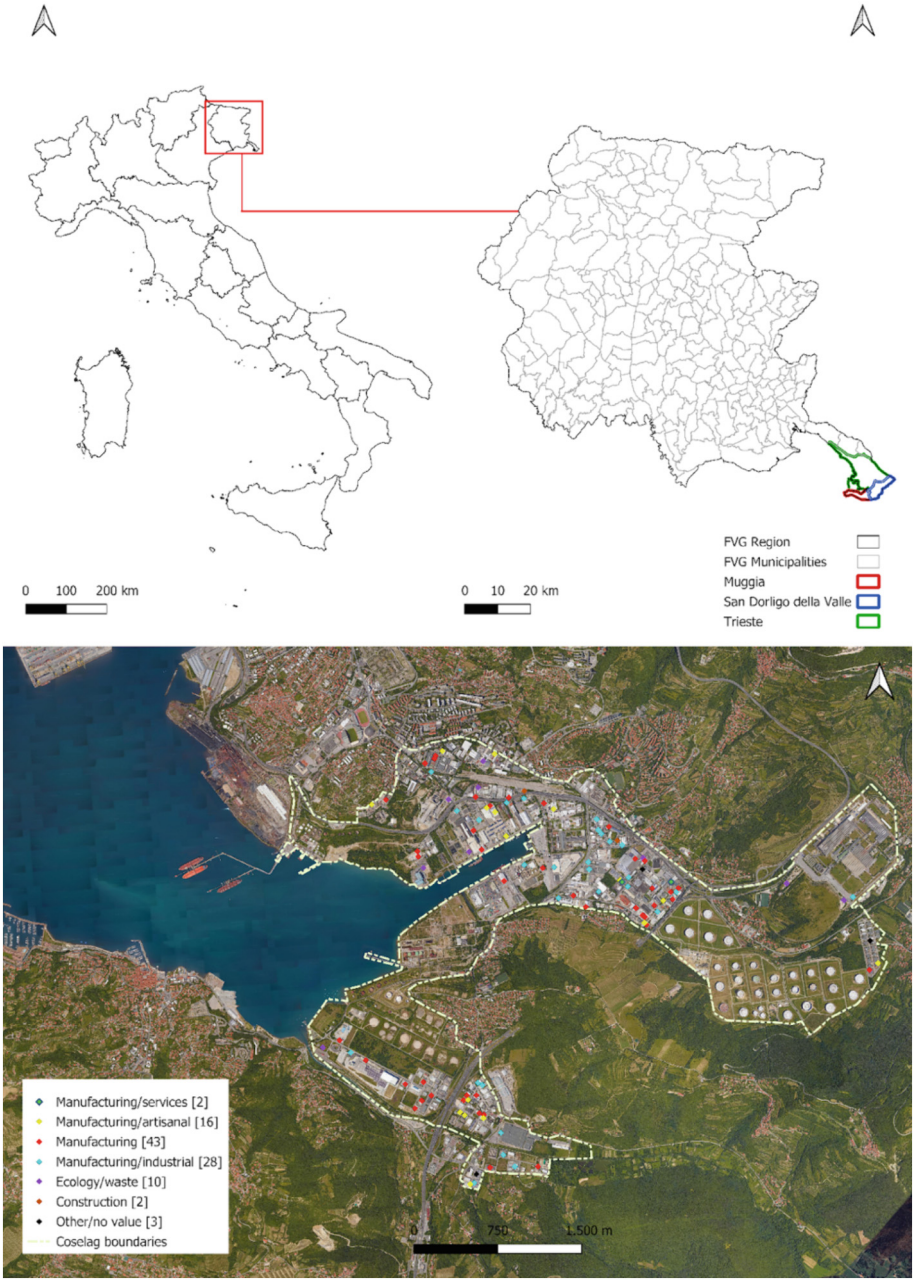


Fig. 4. District of the Industrial Zone's companies (Personal Elaboration, 2024)

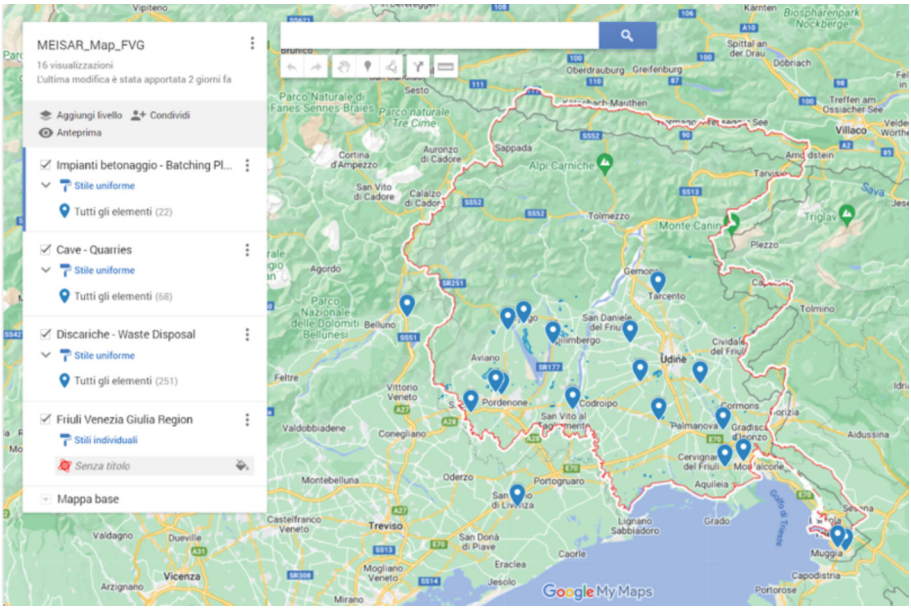


Fig. 5. The MEISAR Map FVG

Then, thanks to the development of this IS strategy, unused parts were categorized as by-products, stored, and in most cases, given as a gift to individuals for food use, to farmers for agricultural purposes, or, at worst, disposed of as waste.

As stated by the interviewee, the study of symbiosis has been highly advantageous in multiple ways, including environmental and economic ones, in this context. Firstly, this synergy has allowed the company to remove lemons continuously without having to find someone to give them away or occupy warehouse space. It turned out to be an optimal choice from the ethical and environmental point of view since, as indicated by the interviewee, dispose of lemons was seen as a real waste.

4.2 Circular Economy in the Industrial Zone of Trieste

As part of this research, a meeting was organized with the entrepreneur of a company located within the consortium's district which carries out the activity of "storage, processing by volume adjustment, the treatment of special waste, sorting, shredding and volumetric conditioning of special waste similar to urban. Construction and operation of plants for the production of heat and electricity. Management of areas, warehouses, terminal yards, handling, storage, storage, distribution, and handling of goods in general. Management of commercial warehouses of products or goods in general.

The interview was carried out due to the fact that the company began the demolition works of one of their buildings which occupies approximately 26,000 m^2.

From the waste generated by this demolition, the company will try to recover most of the reusable material, for the construction of their new plant that will rise a few kilometers

from the old. In doing that, the company is taking different steps to implement the circular economy practice, as:

- The analysis of all the materials present as iron, asbestos etc. obtaining a detailed mapping of the whole area.
- Strip-out operations, which take place during demolition and involve the preventive removal of all elements from the building structures, which must be handled differently. This phase enables the effective management of waste materials by directing them towards the proper disposal and recovery processes, preventing dangerous waste from being mixed with inert and recoverable materials [19]
- Remediation of asbestos in other areas and then the cement analysis in order to establish their typology.

The demolition of the area mentioned will only take place after these interventions are completed.

5 Conclusion

In the near future, it is expected to focus more research on synergies between companies within the Industrial Area of Trieste, trying also to have a more in-depth collaboration within the related companies. This implies the study of the possibilities of exchange of by-products, resources and skills between the different companies present in the territory.

The primary objective will be to identify how these synergies can contribute to the creation of a more robust and sustainable local economic ecosystem.

With a greater focus on synergies research, the aim is to promote greater efficiency in the use of available resources and to reduce the environmental impacts associated with industrial activities. This approach can not only lead to a better management of resources, but also to a greater competitiveness of companies in the industrial area of Trieste.

Through closer collaboration between companies and a sharing of resources and skills, it is hoped to create a more dynamic and resilient economic environment. This could encourage the development of new business opportunities and innovation, thus helping to consolidate Trieste's position as an important industrial and commercial hub in the region.

The limit of this work lies in its evolution. In fact, it is a developing project which, through its implementation, will enable us to obtain more precisely data to assess the benefits of this approach in an industrial area. In addition, it will provide us with an holistic view of the positive implications that can be achieved, paving the way for future decisions and actions to promote good circular practice.

Acknowledgments. This publication was produced while attending:

• PhD programme in Circular Economy at the University of Trieste, Cycle XXXVIII, with the support of a scholarship financed by the Ministerial Decree no. 351 of 9th April 2022, based on the NRRP - funded by the European Union - NextGenerationEU - Mission 4 "Education and Research", Component 1 "Enhancement of the offer of educational services: from nurseries to universities" - Investment 4.1 "Extension of the number of research doctorates and innovative doctorates for public administration and cultural heritage".

• a period of study and research at Co.SELAG - Consorzio di Sviluppo Economico dell'Area Giuliana.

Conceptualization, methodology, formal analysis, materials and resources, data curation and validation: all authors. In particular: Sinatra wrote Sects. 1.1, 3, 4 and 4.2; Borruso wrote Sects. 1.2 and 2; Primiceri wrote Sects. 4.1 and 5.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article. Confidential collaboration with the project companies does not allow the dissemination of localization and quantitative analysis of the case studies developed.

References

1. Geisendorf, S., Pietrulla, F.: The circular economy and circular economic concepts - a literature analysis and redefinition. Thunderbird Int. Bus. Rev. **60**(5), 771–782 (2018)
2. Savi, P.: Industria 4.economia circolare: possibili convergenze e implicazioni territoriali. Società di Studi Geografici **19**, 697 (2021)
3. Balletto, G., Borruso, G., Mei, G., Milesi, A.: Economia circolare, gestione dei rifiuti da costruzione e demolizione e produzione di Aggregati Riciclati. Il progetto MEISAR–Un'applicazione alla Sardegna. Bollettino dell'Associazione Italiana di Cartografia (2020)
4. Borruso, G.: Port-City relationship in the era of hybridization. A development model. J-Reading-J. Res. Didactics Geogr. **11**(2), 125–137 (2022)
5. Rodrigue, J.P.: The Geography of Transport Systems. Routledge, London (2020)
6. Vallega, A.: Geografia delle strategie marittime: dal mondo dei mercanti alla società transindustriale. Mursia, Milano (1997)
7. Vigarié, A.: Economia marittima e geostrategia degli oceani. Mursia (1992)
8. Musso, E.: Città portuali: l'economia e il territorio. FrancoAngeli (1996)
9. Friedmann, John: On the contradictions between city and countryside. In: Folmer, H., Oosterhaven, J. (eds.) Spatial Inequalities and Regional Development, pp. 23–45. Springer, Dordrecht (1979). https://doi.org/10.1007/978-94-017-3046-4_2
10. Lloyd, P.E., Dicken, P.: Location in space. A theoretical approach to economic geography (1977)
11. Weber, A.: Uber den standort der industrien, Tubingen. English translation by CJ Friedrich (1929) Theory of the Location of Industries. (1909)
12. Von Thünen, J.H.: Der Isolierte Staat in Beziehung auf Landwirtschaft und Nationalökonomie, Puthes, Hamburg (1826)
13. Balletto, G., Borruso, G., Mei, G.: Location theory and circular economy. Demolition, constructions and spatial organization of firms–an applied model to Sardinia Region. The case study of the New Cagliari Stadium. In: Computational Science and Its Applications–ICCSA 2019: 19th International Conference, Part III 19, pp. 535–550, Saint Petersburg (2019)
14. Balletto, G., Borruso, G., Mei, G., Milesi, A.: Strategic circular economy in construction: case study in Sardinia, Italy. J. Urban Plann. Dev. **147**(4) (2021)
15. COSELAG. http://www.coselag.it/. Accessed 25 Mar 2024
16. Piano Industriale 2022–2024. https://www.regione.fvg.it/rafvg/export/sites/default/RAFVG/economia-imprese/rilancimpresa/FOGLIA10/FOGLIA1/allegati/COSELAG_PI_22_24.PDF. Accessed 06 Feb 2024
17. Interreg ECOLE Homepage. https://www.alpine-space.eu/project/ecole/. Accessed 04 Feb 2024

18. Camera di Commercio Varese. https://www.va.camcom.it/pagina881_classificazione-delle-attivit-economiche-ateco.html. Accessed 16 Apr 2024
19. Strip out o demolizione selettiva, la nuova frontiera della riqualificazione edilizia. https://www.ecoopera.coop/it/interventi-di-bonifica/strip-out/#:~:text=Le%20operazioni%20dette%20%E2%80%9Cstrip%2Dout,essere%20gestiti%20in%20modo%20differenziato. Accessed 10 Apr 2024



Smart City-Port Relationship: A Circular Port City Development Model for Trieste

Giuseppe Borruso[1(✉)], Andrea Gallo[1,2(✉)], Francesca Sinatra[1(✉)], Ginevra Balletto[3(✉)], and Salvatore Dore[1(✉)]

[1] DEAMS - Department of Economics, Business, Mathematics and Statistics "Bruno de Finetti", University of Trieste, Via A.Valerio 4/1, 34127 Trieste, Italy
giuseppe.borruso@deams.units.it, {andrea.gallo3, francesca.sinatra}@phd.units.it, salvatore.dore@amm.units.it

[2] Department of Economics, Ca' Foscari Venezia University, Dorsoduro, 3246, 30124 Venezia, Italy
and.gallo@unive.it

[3] DICAAR - Department of Civil, Environmental Engineering and Architecture, University of Cagliari, Via Università 40, 09124 Cagliari, Italy
balletto@unica.it

Abstract. Ports as sea-land interface nodes have always been key crossroads for goods and people and for the diffusion of innovation. The recent challenges descending from sustainability need to consider the interaction among the city and its port, particularly in their capacity of playing pivotal roles in shaping the sustainable economic development of their regions, exerting a substantial impact on well-being and overall quality of life, representing an opportunity for implementing Circular City concepts. Achieving this goal depends on the use of appropriate development models for production and consumption, with a focus on interactions within the urban and territorial framework. The implementation of the concepts belonging to the circular economy into the port context, expressed within gateway ports, by their nature strongly embedded within an urban and regional framework, is nonetheless a subject yet to be more deeply investigated. The present research is based on an analysis performed combining different models developed in time to study the city-port relation (Bird's Anyport model) as well as location in space (Weber model of industrial location) within a circular framework. Operationally, a city-port interference and interaction matrix is developed, to analyze the areas of potential development of the circular activities, in particular those related to building maintenance, demolition and reconstruction. These in particular spatial analytical and mapping instruments are also implemented to realize and examine a GIS database for the model's application. The study was implemented to introduce some considerations for the development strategies into the framework of the city-port relation for the study area of Trieste, Italy.

Keywords: First Port-City Relationship · Smart Ports · Smart Cities · Circular Economy

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 384–400, 2024.
https://doi.org/10.1007/978-3-031-65238-7_26

1 Introduction

Ports represent strategic nodes of interchange for trade flows at global and regional scales [1], both representing interfaces between the maritime component (foreland) and the land one (hinterland), allowing circulation of goods and people, and representing important drivers of local development. Historically, port activity brought local employment and the dissemination of knowledge created by the sharing and contamination of people and industries in one place [2, 3]. Also, negative externalities and impacts are associated with the presence of ports in urban settings [4, 5]. Despite the fact that the importance of ports to national economies and global trade is clear, there has been a decline in the benefits associated with ports at the local level [6, 7]. These can be summarized in an increase of the negative environmental impacts, the relocation of port-related activities, the decrease in local employment and the increasing use of international - rather than local - inputs. The major drivers of such changes followed globalization and technological innovations, such as naval gigantism, mechanization of port activities, and increased containerization, with a consulting reduction in the number of people directly employed in port work, as well as a higher integration of the supply chain, de facto making ports as crucial nodes in the global supply networks [8–10].

In addition, levels of economic, institutional, and infrastructural integration between ports and cities have declined, with ports serving both consumers and producers over much larger geographic and hinterland areas [11].

In this sense the adoption of circular economy (CE) principles in the port context has become increasingly central to the organization of development processes in port areas. The CE is defined as an economic system that replaces the concept of 'end-of-life' with that of reuse, recycling and the recovery of materials in production/distribution and consumption processes. This can operate at three different process scales: at the micro level - through product and business process innovation - or at the macro level - city, region, nation and beyond -, with the goal of achieving sustainable development [12, 13]. Circular economy principles thus view scrap and waste as resources that can be recycled and reused [14, 15]. Focus on environmental issues is particularly relevant not only in terms of port operations but also with regard to industrial activities in ports and planning and expansion initiatives for ports.

The introduction of these principles in the port environment is a topic currently central to the scientific debate, as well as an issue being tackled by port authorities and also local municipalities proximal to port areas. Nonetheless, several studies focused narrowly on the micro level. From this perspective, this study proposes to investigate the dynamics of development in port-city relations from a circular economy viewpoint applied at the macro level, thus going on to consider waste materials and aggregates as second raw materials to be used within the various port infrastructure development projects.

In this study the port of Trieste is analyzed as a specific case study, taking into consideration what are the main infrastructural work planned by the Port Master Plan and the Strategic Operational Plan of the Eastern Adriatic Sea Port System Authority, and implementing on these development trajectories the considerations about the reuse of secondary raw materials.

The contribution presented, is organized as it follows. In paragraph 2 (Materials) the city-port relations are briefly examined, together with the concept of circular economy and industrial symbiosis. Paragraph 3 (Methods) roots the research into classical models of city-port evolution (Bird) and industrial location (Weber) both updated to host the changes that intervened in more recent times and particularly in hosting circularity concepts. The operational aspects of the symbiosis matrices area also introduced. The analysis of the case study follows in paragraph 4 with a focus on Trieste (Italy) port area analyzing the potentials of introducing circularity in port-related works. Paragraph 5 host results and discussion, followed by conclusions in paragraph 6.

2 Materials

2.1 The Framework of the Port-City Relationship

City-port relations are characterized by means of a wide set of interdependencies among the evolutions of port and urban forms. This relation is clearly reflected in the evolution of coastal cities, which have often found their development closely linked to the surrounding port activities. Several studies in the literature are aimed at analyzing the development of city-port relations diachronically, that is, as the result of a process of historical evolution [2, 16–18]. Such processes were also coupled with the development of industrial activities, followed then by logistic ones, in these coastal areas, benefitting from the ideal location in proximity of important nodes, shaping the characters of ports and their cities. [4, 19].

The heavy industry was located in areas originally peripheral to major urban centers [19], benefiting of cost efficiency in the access to materials and to the distribution systems. In parallel, urban sprawl with the relocation of businesses to industrial settings in backport areas, resulted in the abandonment of industrial port functions, leaving spaces vacant [4, 20], becoming the object of long-term 'waterfront redevelopment' [21, 23, 24]. Ports however evolved in developing inner harbours and inland terminals, not only affecting the urban dimension of the waterfront, expanding inner industrial and logistics zones to support port activity, with important urban redevelopment processes, and the development of potential conflicts between urban and port uses [22, 23]. Port cities, known as a densely populated area, experimenting with the rapid development of ports and their specialization and expansion, have been facing a wide range of ecological challenges, including environmental pollution, leading to a need for a greater attention to the dangers arising from this co-existence.

2.2 The Future of the Port Beyond the Port: Circular Economy and Industrial Symbiosis Transition

The CE represents a business model within which economic growth is closely related to environmental impact, through the promotion of more resilient production patterns and the use of renewable materials [26]. Attention to environmental impacts is also playing an increasingly important role in maritime transport today, in relation to pollution and emissions from ships that undermine the sustainability of ports and the neighboring

ecosystem [27]. The industrial symbiosis is part of the context of industry 4.0 and has a strategic role in the framework of sustainable development as it facilitates the creation of digital networks, logistics and supply chains through an integrated management of resources. This is done on one side allowing the reduction of waste, by means of processing, reuse, and on the other side favoring the implementation of related businesses in terms of the use of one company's waste or by-product as inputs for other ones. Industrial symbiosis plays a central role in ecological and energy transitions as it becomes a pivotal point in the creation of a circular model [28].

Being ports aggregators of different port and logistics related activities, as well as industrial and service ones, as a consequence, the passage towards a circular economy represents a challenge for the ports all over the world [29]. There are different strategies that can be used in ports, from the reuse of materials and energy to initiatives put in by small enterprises or start-ups [29].

In the last decades, ports have worked to improve their sustainability through Corporate Sustainability (CS), which has become a key factor in defining strategies for the port authorities at the global level. The port management, traditionally geared to profit, is moving towards more sustainable practices, also because of the increased media pressure on environmental issues related to ports. However, the shift to more sustainable practices is hampered by the lack of clear global regulations and the complexity of the public-private dynamics which characterize many port authorities. Ports must balance economic growth with the reduction of negative environmental impacts, considering a wide range of environmental and externalities generated from their activities [30]. In summary, the transition to a circular economy in ports is based on three main pillars: energy recovery, recycling and the creation of new flows of value goods. The industrial symbiosis (IS) emerges as a key strategy, allowing collaboration between ports, industries and cities to reuse waste and materials. Moreover, the adoption of the circular economy in the ports implies a greater attention to all the services, which can influence the circular transitions in industries that use their services. It is important to link the circular economy with industrial symbiosis and port-city dynamics to develop new circular commodity flows. Certainly, the application of the circular economy must extend to processes and infrastructure, influencing spatial planning and product design [29].

3 Methods

The multi-faceted issue of the application of CE principles in the city-port dyad, by implementing the industrial symbiosis on one side, and a renovated city-port symbiosis on another side, implies rooting the research and its applications down into a theoretical framework that combines traditional theories and models within an extended sustainable environment. At the same time the theoretical framework needs to be put in action on real case studies. In such a sense, a workflow and the application of ad-hoc developed instruments need to be implemented and presented.

From the theoretical and methodological point of view, the analysis is performed developing a conceptual model that considers the city-port relationship in the framework of the Bird's Anyport development model, in its evolution of the hybridized functions played within the cities and their ports. The model is integrated with the evolution in

a circular framework of Weber's location theory, expanded to consider circularity in location choices. This is implemented by means of developing an interaction matrix among city-port interferences and interactions, as well as locating in space the potential activities and sites connected to a testbed case study, such as that of the implementation of circular activities in construction in the Trieste port area [31, 32].

Such approach considers circularity in the development of the city-port relationship, as in the recent development regarding the Anyport model [26, 33] presented in Sect. 3.1. These reflections are subsequently extended through the development of a matrix of circularity and industrial symbiosis in the framework of the city-port relationship, presented in Sect. 3.2: this is divided into two sub-sections, the first dedicated to presenting the implications on circularity of spatial location with respect to the places of supply of materials and final destination markets, and the second in which the city-port symbiosis matrix is presented. The methodology presented below is summarized in Fig. 1.

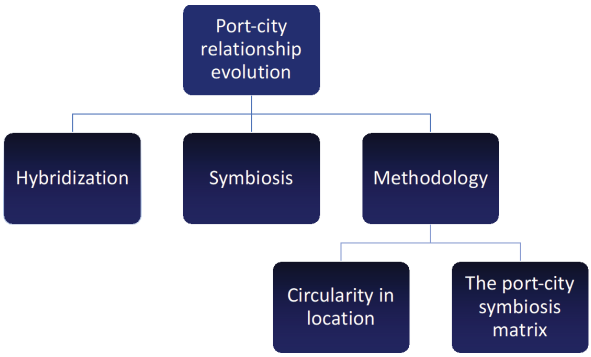


Fig. 1. Framework of the evolution of port-city relationship and methodology: circularity in location and port-city symbiosis matrix

3.1 Ports and Their Evolution. The Anyport Model with Hybridization

Port's evolution as previously introduced in paragraph 2.1 was synthesized and modeled within a model developed by Bird [17, 34] in which the evolutionary stages of cities and ports were considered as common to 'any' city and port - from that, the name 'Anyport' - and therefore presenting similarities among the different contexts. The evolution in ports was summarized by Borruso (2022) [34] in a proposal to evolve furtherly from the Anyport model, summing up a further stage of development, that of the hybridization of the functions, both from the port and from the city points of view. The evolutionary path taken by the city-port dyad in time led to different moments of alternatively tightening and loosening of the relations between the two parts. The latest stage in the model of development followed by ports, that of specialization, seemed to mark an important divide between ports and cities, given the exchanged and modified role of ports of playing their function servicing more a hinterland consisting on the port regions and even farther destinations, in case of the gateway ports, and servicing the maritime foreland, in case of hub ports.

The more recent evolution of ports, however, which was named as that of 'hybridization', seems to be changing and renewing the existing relationship between ports and their cities, as functions tend to be more mixed. This happens not just within the terminals, but also in the former port areas, as on the urban waterfront, where urban and port functions mix and coexist - cruise ships and passengers use often same parts of the city as citizens and city-users - or as in the peripheral and semi-peripheral areas of the city, where port-related functions are more and more moved in order to free valuable space on the docks. Dry ports and inner terminals in fact move far from the shoreline and docks, to allow handling, warehousing, train composition and other transport and logistics-related operations [25, 34].

3.2 Circularity in Location and the Port-City Symbiosis Matrix

As from the previously mentioned considerations, mixed functions in different areas, both proximal to the waterfront and in inner areas, have recently taken place and challenge urban and port development, in terms of positive and negative externalities. The analysis of the port and city evolution in terms fostering circularity in the economic development towards sustainability, there is a need to observe the different spatial subjects, as urban areas, waterfronts, peripheries, semi peripheries, suburbs and the proximal port and port related areas, within a broader planning and programming framework capable of considering together circularity and hybridization.

Circularity in Location. As a matter of example, there is the need to develop circular development synergies in the port and urban sphere in relation to the development of planned major infrastructure works. Such elements appear as belonging to an innovative perspective within the theoretical framework of a circular economy of construction and manufacturing, particularly in terms of recycled aggregates as secondary prime materials, thus reevaluating a traditional model of industrial location considering contemporary circumstances. This implies inserting circularity within Weber's studies on industrial location [17], revisiting the ideal location of manufacturing facilities connected to transport costs from and to energy, materials and marketplaces. From the original model, that foresaw the minimization of transport costs by locating manufacturing plants near either to raw material and energy sources or to markets, according to their weight into the final products and the relative transport costs. In a circular economy framework, the spatial separation among 'resources', 'energy', and 'market' becomes quite naive, as second prime materials are inserted as resources, and the same 'market' can become a place of origin of resources - in case we consider reusing and recycling of materials. Furthermore, the same plants can be located in proximity of the 'market' - i.e., a demolishing and reconstructing building or compound can represent a 'market', being the place where a new construction will be done, a place of origin of 'materials' and, also the preferred location for a batching - treatment plant - a 'firm' in Weber's theory [27, 31]. This led to the definition of an extended version of the model, to include, as materials' locations, the places of origins of recycled construction waste [35]. In such a sense, proximity becomes important and relevant particularly to foster a functional and locational integration both within the same production system and among different productions involving reuse of waste and byproducts. Apart from the theoretical framework of the 'extended Weber

locational model', a necessary stage is that of locating in space the potential places of origins of the materials involved in the circular production: attention is to be paid to the port itself as a generator, for example, of secondary raw materials. For this reason, the approach will be linked to the methodology used for the MEISAR –"Materials for Sustainable Construction and Infrastructure: The Recycled Aggregates"- project. The circular economy's key principles can be applied effectively with clusters that involve companies that recycle construction and demolition waste, quarries, and batching plants.

The port-city symbiosis matrix. The research begins by integrating various analyses, such as investigating and organizing planning tools at both a strategic and urban level and linking them to industrial and logistical organizational aspects in a circular perspective.

The methodological approach aims to generate a synthetic matrix that encompasses planning and governance tools, while also incorporating spatial dimensions and circular objectives. In addition, the approach aims to develop a synthetic matrix that takes into account the different planning and governance tools, spatial dimensions, and the existence of circular purposes.

Planning tools have an impact on a range of space-related issues, including development and approval state, spatial and administrative dimensions, overall characteristics of the application (industrial, urban, port/logistics, etc.), and the presence of circular shares in relation to the aforementioned spatial features and frameworks.

The outcome is a matrix for evaluating urban-port performances that provides a synthetic picture of their summaries and characterizations, in order to exploit the coexistence of planning and integration tools or potential conflicts arising from the different uses of urban and port areas (Fig. 2).



Fig. 2. Framework of Port City Symbiosis. Port and urban planning and the planning tools. – Source: Personal Elaboration [25]

4 Case Study. Port City Hybridization as a Driver of Circular Economic Development: The Case of Trieste

4.1 Port of Trieste, Waterfront, and Future Development

The Port of Trieste, located at the northern tip of the Adriatic Sea, serves as a crucial logistical node for intra-Mediterranean trade and strategic connections between Central-Western Europe and the Middle East. Functioning as an international port, it handles a

significant portion of its traffic through global routes [37]. In 2023, it ranked as Italy's top port in terms of cargo volume, managing over 57 million tons of goods, with 65% comprising liquid bulk commodities, primarily petroleum products. Recent years have witnessed notable growth and heightened commercial activity at the Port of Trieste, capitalizing on its inherent geographic advantages, including a seabed depth of approximately 18 m and a well-developed railway network connecting to logistics hubs across Central and Eastern Europe [38].

The analysis on potential circular activities in port areas is performed considering the development trajectories of the port of Trieste, the Port Master Plan provided by the Port Network Authority of Eastern Adriatic Sea, that manage the ports of Trieste and Monfalcone, was taken into consideration in Fig. 3 the Trieste port's expansion framework as in the port master plan is presented in order to identify the planned areas of development in the short to medium term.

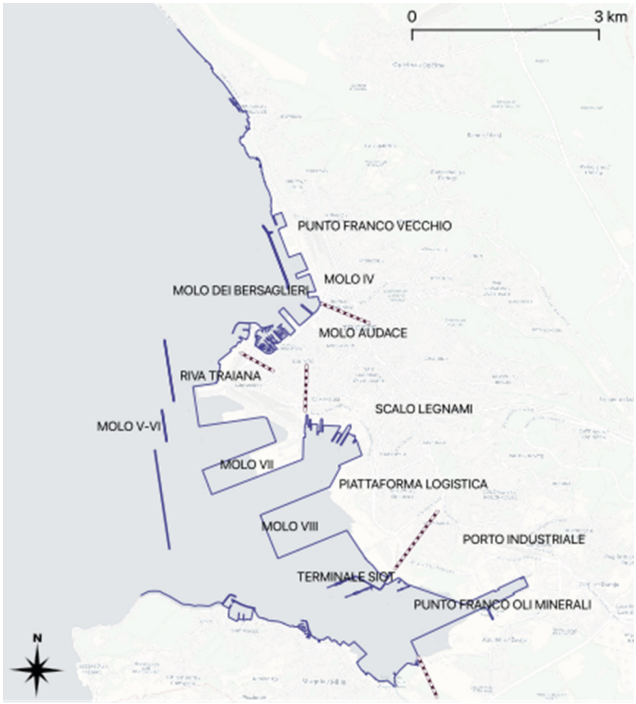


Fig. 3. Port of Trieste, coastline, and future development Source: Personal Elaboration on Port Authorities data

In particular, the area located close to the Logistic Platform (Piattaforma logistica in the map) is earmarked as the first strategic infrastructure to be realized, both as the root for the development of the new container terminal Pier VIII (Molo VIII) and for the development of land infrastructures supporting the road and rail connections supporting the logistics activities of all the terminals. The realization of Pier VIII, while not forthcoming in the short run, represents the pivotal strategic work for the expansion

of the productive capacity of cargo handling by the Port of Trieste, with a quay with an estimated size of about 88 thousand square meters, a length of 860 m and a width of 100.

Other works either planned or ongoing include the construction of a new multipurpose terminal in the southern part of the port, in an area that was historically occupied by 'l'Aquila' refinery plant, and the expansion of Pier 'VII', the current container terminal at the Port of Trieste. The design of these works is presented in Fig. 4 below.

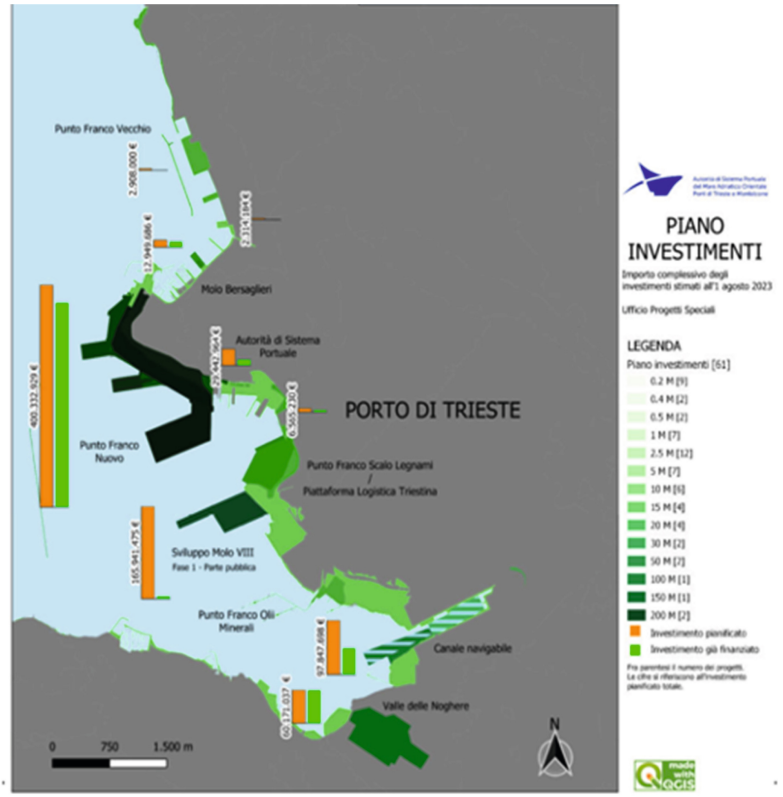


Fig. 4. Investment from the Three-Year Port Plan 2021–2024 – Source: Port Authority of Trieste

4.2 Investments from the Three-Year Operating Plan

To implement circularity within the port framework, the starting point is the plan of investments allocated in the framework of the three-year operating plan, divided into 6 different items, which are: rail infrastructure, port infrastructure, investments in energy and environment, investments in green ports, allocations for heritage conservation, and finally other planning services (Table 1).

Table 1. Summary of investments divided by macro-categories Source: Port Network Authority of the Eastern Adriatic Sea, Three-Year Operating Plan 2021–2024.

Categories	Amount ('000 Euro) Three Year Operating Plan 2021–2024
Railway Infrastructure	284.266 €
Port Infrastructure	243.393 €
Energy and Environment	33.952 €
Green Ports	35.231 €
Heritage conservation	19.043 €
Supplies of Services	7.260 €

5 Results and Discussion

Circular economy issues have been tackled following different steps that will need more in-depth analysis. The analysis in particular produced three main results in terms of obtaining the 'building blocks' of circularity in port-city relation. In the present stage, the most promising part of issuing circularity action is relatable to construction activities, that imply considering waste from demolition as potential sources of secondary prime materials and therefore capable of activating circular economic interaction and symbiosis.

5.1 Identification of the Investments and Their Potential in Circularity

When considering the Three-Year Operating plan and the investments, specifically, in this phase, the focus will be on the investments included under the heading "Port Infrastructure". This item has been explored in depth because, from the perspective of circularity of production processes, we can identify demolition and waste disposal as a source of secondary raw materials to be processed in waste treatment plants. At the same time, the construction of new infrastructure works implies a demand for construction raw materials. Under a circularity profile then, it could be hypothesized that demolition works, dredging and the production of large amounts of waste, could generate waste materials flows that once processed, would be transformed into raw materials to be used in the construction of new infrastructure works such as the construction of the new yards and dock as presented in Table 2. Under this perspective, and following the Meisar approach [39], the locations of caves, batching plants, landfills, recycling plants, quarry concessions and waste treatment plants close to the port context were considered, due to highlight not only the places of origin of the different raw materials, but also the locations where it could be processed in order to re-integrate it into circular construction production cycles.

Thus, we can see that most of the investments included in the Port of Trieste's Three-Year Operational Plan are aimed at improving logistical and environmental efficiency. In particular, for the share of investments aimed at increasing rail traffic through the implementation of systems related to this mode of transport, to investments in 'green ports' but also with a series of investments aimed at improving energy performance and

Table 2. Summary of investments in infrastructure Source: Port Network Authority of the Eastern Adriatic Sea, Three-Year Operating Plan 2021–2024.

Categories	Amount (‘000 Euro) Three Year Operating Plan 2021–2024
Port Infrastructure	
Extraordinary maintenance work on the dock at the Scalo Legnami behind the I extension and the extension of Pier II - Prog. 1897	1.501,95 €
Extraordinary maintenance work on the facades of warehouses Nos. 85–86-87–88-89 and interior warehouse No. 87 handed over to the Guardia di Finanza	1.450,00 €
Partial resurfacing work at the port of Monfalcone	1.350,00 €
Work on the construction of a new electrical cabin in the New Free Point of the Port of Trieste - Prog. 1900	2.800,00 €
Extension work on the root of Pier VI of the New Free Point of the Port of Trieste - Prog. 1801	18.307,21 €
Completion of the “east” forecourt at the former San Marco Arsenal: repaving and preparation of new sheds in the remaining area between the sea and the property boundaries	3.000,00 €
Extraordinary maintenance work on the facades of warehouses Nos. 85–86-87–88-89 and interior warehouse No. 87 handed over to the Guardia di Finanza	1.450,00 €
Renovation work on the facade and roof of Warehouse No. 41 - Trieste Maritime Station at the Bersaglieri Pier - Prog. 1838	2.760,00 €
Consolidation works of the South Rizzo Dam of the port of Trieste - Prog. 1816	6.724,00 €
Intervention components in the project of infrastructural and functional modernization of the container terminal at Pier VII in the Port of Trieste - Prog. 1949	100.500,00€

(*continued*)

Table 2. (*continued*)

Categories	Amount ('000 Euro) Three Year Operating Plan 2021–2024
Port Infrastructure	
Preparatory works for the establishment of logistic and industrial activities in the Noghere area, with a view to integration with the Noghere port terminal under construction	60.000,00 €
Partial dredging of the Noghere Terminal in the Port of Trieste, including dredging of the service channel and connection to the road system - Prog. 1948	45.000,00 €

the creation of a system of cold ironing of the docks aimed therefore at lowering the polluting emissions of ships at the docks, which we remember to be the main item of impact in terms of emissions in port contexts for a share that averages between 70 and 80% of total port emissions [4]. Also important in the plan are works to upgrade buildings and warehouses in the port context, aimed at increasing the port's energy efficiency.

5.2 Circularity in Location

With reference to the potentials of realizing local industrial symbiosis, considering the case of construction and reuse of first and second raw materials, an example of a workflow for reorganizing data for realizing symbiosis is proposed. At present locating in space the monetary values implied that can be involved in a circular process does not seem feasible, being the planned projects not yet in an advanced stage of implementation and, therefore, the materials' requirements not being clear at present.

A further step in setting the framework for circularity is georeferencing the potential economic subjects that can be involved, to optimize location. To do that, we propose the construction of a MEISAR_Map, recalling a previously implemented project [30, 38] in this context linked to Weber's theory, adapting it in a circular perspective, applying this model to the case study of the Port of Trieste, placing the attention on the port as generator of raw and second materials. The importance of a spatial constraint cannot be overstated, as the distance between the plants and the location where secondary raw materials are used must not exceed 30 km.

Both fieldwork and surveys were necessary to accurately position the elements in space, ensuring they were harmonized within a unified reference system.

Different sources for geocoding points were used. Landfills were derived from the Friuli Venezia Giulia website. Data were updated to 2024 and organized to be displayed on a Google MyMaps platform, called "MEISAR_Map_FVG", to keep all of the authors and participants of the MEISAR project up-to-dated on the different stages of the research (Fig. 5).

The MEISAR_Map_FVG is not a proper GIS - Geographical Information System, nonetheless it is based on preparatory work involving data preparation, organization, and elaboration of geographical data from multiple sources, by means of the QGIS platform. Considering the data realized and loaded onto the MEISAR_Map, we georeferenced all the players at regional level involved into the different processes of production, quarries, batching plants, waste disposal sites (Fig. 2).

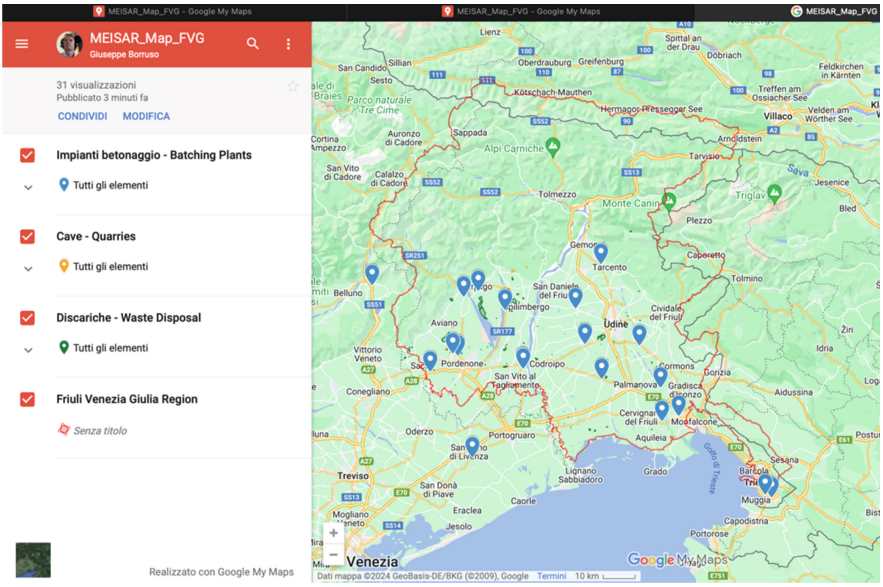


Fig. 5. The Meisar Map for the Friuli Venezia-Giulia Region https://bit.ly/Meisar_Map_FVG - Source Author's elaboration in Google MyMaps

5.3 The Port City Symbiosis Matrix

A further step in the evaluation and planning of circular actions in the city-port framework is that of considering a matrix where urban planning tools and the different port and city spatial components are matched. The above-mentioned analytical matrix is therefore filled considering overall planning tools insisting on the different areas of the port-city dyad. The planning tools are related to port and urban planning, the mobility plans and the industrial ones, including also the specific case of the Free Zones.

Considering the different levels of adoption of the planning instruments, the port and city of Trieste at present are characterized by a wide set of instruments usable and applicable to produce their effect over territories, and considering the different levels, as (urban) waterfront, port areas and extensions, semi-periphery and periphery. In most of the sub-areas considered, plans appear to be in an advanced stage of adoption, while only periphery appears still little covered by the ordinary urban planning tools, particularly in terms of transport topics (Fig. 6)

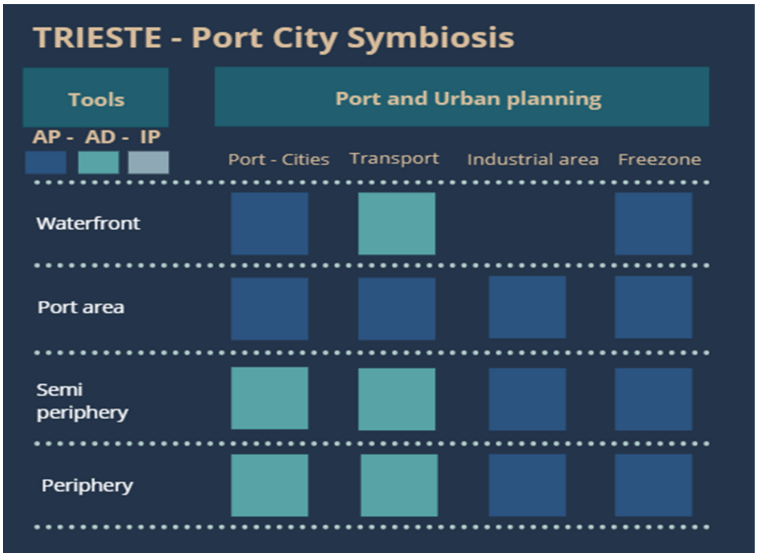


Fig. 6. The Port-City symbiosis matrix – Trieste - Source: Author's elaboration [25]

6 Conclusions

Given the complex framework in which ports find themselves within the circular transition, applying circular strategies and trying to mitigate the negative effects caused by port activities on the ecosystem constitute a crucial node.

If the port cities of the future are to be sustainable, ports must aim to reduce their negative am- environmental impacts as much as possible while increasing local economic and social benefits. City-port interaction in relation to waterfront development and industrial development are key strategies through which ports can generate significant economic benefits for the backwater area [7].

So, we can highlight how city-port relations represent an eloquent example of symbiosis between economic processes and relative physical places. Urban evolution has influenced port planning and vice versa, creating a spatial and temporal continuum in which cities and ports influence each other, adapting to the changing needs of commerce and society [27, 28].

The paper showed how practices such as optimization of the use of resources, reduction of the amount of waste, materials recycling and the adoption of more resilient and green technologies can improve both ports' operational efficiency and reduce greenhouse gas emissions and pollutants.

Consequently, this approach also leads to economic efficiency, through the creation of long-term benefits and rise of new business opportunities in fields as sustainable material management and resource savings.

Despite this, collaboration between port authorities and different stakeholders involved is essential in order to develop ad hoc strategies which take into account needs and challenges of local communities, maximizing the benefits for both economy and environment systems.

Acknowledgments. This publication was produced while attending PhD programme in Circular Economy at the University of Trieste, Cycle XXXVIII, with the support of a scholarship financed by the Ministerial Decree no. 351 of 9th April 2022, based on the NRRP - funded by the European Union - NextGenerationEU - Mission 4 "Education and Research", Component 1 "Enhancement of the offer of educational services: from nurseries to universities" - Investment 4.1 "Extension of the number of research doctorates and innovative doctorates for public administration and cultural heritage".

Conceptualization, methodology, formal analysis, materials and resources, data curation and validation: all authors .

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

References

1. Hoyle, B.S., Pinder, D.A.: European Port Cities in Transition. Belhaven Press, London (1992)
2. Vallega A.: The Changing Waterfront in Coastal Area Management. FrancoAngeli, Milano (1992)
3. Hoyle, B.: Global and local change on the port-city waterfront. Geogr. Rev. **90**(3), 395–417 (2000)
4. Saz-Salazar, S.D., García-Menéndez, L., Merk, O.: Port–city relationship and the environment: literature survey and methodological approach for project appraisal in presence of environmental externalities. J. Urban Planning Dev. **141**(3) (2015)
5. Hall, P.V., Jacobs, W.: Why are maritime ports (still) urban, and why should policy-makers care? Marit. Policy Manag. **39**(2), 189–206 (2012)
6. Musso E.: Città portuali: l'economia e il territorio. FrancoAngeli, Milano (1996)
7. Musso E., Ghiara H.: Ancorare i porti al territorio. Dai traffici alla marittimizzazione. McGraw-Hill, Milano (2007)
8. Vallega A., Geografia delle strategie marittime. Dal mondo dei mercanti alla società transindustriale, Mursia, Milano (1997)
9. Balletto, G., Borruso, G., Campisi, T.: Not only waterfront. The port-city relations between peripheries and inner harbors. In: Gervasi, O., Murgante, B., Misra, S., Rocha, A.M.A.C., Garau, C. (eds.) Computational Science and Its Applications–ICCSA 2022 Workshops: Malaga, Spain, July 4–7, 2022, Proceedings, Part V, pp. 196–208. Springer International Publishing, Cham (2022). https://doi.org/10.1007/978-3-031-10548-7_15
10. Vallega A.: Porti e regionalizzazione: un paradigma sistemico, in "Bollettino della Società Geografica Italiana **10**(8), 577–594 (1979)
11. de Langen, P., Sornn-Friese, H.: Ports and the circular economy. In: Green ports, pp. 85–108. Elsevier (2019). https://doi.org/10.1016/B978-0-12-814054-3.00005-0

12. Dore, S., Gallo, A.: Circular Economy and Reverse Logistics: an analysis of sustainable business models. In Gervasi O., Murgante B., Misra S., Rocha, A.M.A.C., Garau C. (eds), Computational Science and Its Applications – ICCSA Workshops 2023, LNCS vol. 14110, pp. 495–511. Cham: Springer Nature, Switzerland (2023). https://doi.org/10.1007/978-3-031-37123-3_34
13. Courtens, F.M., Haezendonck, E., Dooms, M., Verbeke, A.: Accelerating the circular economy transition process for gateway ports: the case of the Port of Zeebrugge. Marit. Transp. Res. **4**, 100088 (2023)
14. Morgan, F.W.: Ports and Harbours. Hutchinson, London (1954)
15. Sellari, P.: Geopolitica dei trasporti. Editori Laterza, Milano (2018)
16. Hayuth, Y.: Intermodal transportation and the hinterland concept. - Tijdsch. Econ. Soc. Geogr. **731**, 13–21 (1982)
17. Bird J.H.: Seaports and Seaports Terminals. Hutchinson, Londra (1971)
18. Hoyle, B., Charlier, J.: Inter-port competition in developing countries: an East African case study. J. Transp. Geogr. **3**(2), 87–103 (1995)
19. Goss, R. O.: Advances in Maritime Economics. CUP Archive (1977)
20. Vigarie, A.: Maritime industrial development areas: structural evolution and implications for regional development. In: Hoyle, B.S., Pinder, D.A. (eds.) Cityport industrialization and regional development: spatial analysis and planning strategies, pp. 23–36. Pergamon, Oxford (1981)
21. Soriani S.: La transizione postindustriale della portualità tra dinamiche di mercato e vincoli-opportunità territoriali in Soriani S. (eds.), Porti, città e territorio costiero. Le dinamiche della sostenibilità, Bologna, Il Mulino, pp. 19–65 (2002)
22. Hoyle, B.S.: The port-city interface: trends. Probl. Examples Geoforum **20**, 429–435 (1989)
23. McCalla, R.J.: Separation and specialization of land uses in Cityport waterfronts: the cases of Saint John and Halifax. Can. Geogr. /Le Géographe can. **27**(1), 48–61 (1983)
24. Norcliffe, G.B.: Industrial change in old port areas, the case of the Port of Toronto. Cah. de Géographie du Québec **25**(65), 237–253 (1981)
25. Borruso, G.: Balletto: The Port-City Relations in the Era of Hybridization. In: Gervasi O., Murgante B., Misra S., Rocha, A.M.A.C., e Garau C. (eds), Computational Science and Its Applications – ICCSA Workshops 2023, LNCS vol. 14110, pp.594–607, Springer -Verlag, Berlin (2023). https://doi.org/10.1007/978-3-031-37123-3_41
26. Circular economy: definition, importance and benefits. https://www.europarl.europa.eu/topics/en/article/20151201STO05603/circular-economy-definition-importance-and-benefits. Accessed 2 Feb 2024
27. Paulauskas, V., Filina-Dawidowicz, L., Paulauskas, D.: The method to decrease emissions from ships in port areas. Sustainability **12**(11), 4374 (2020)
28. Balletto, G., Sinatra, M., Sinatra, F., Borruso, G.: Industrial Symbiosis and Circular Urban Practices. In: International Conference on Innovation in Urban and Regional Planning, pp. 14–24. Cham: Springer Nature Switzerland (2023). https://doi.org/10.1007/978-3-031-54096-7_2
29. Haezendonck, E., Van den Berghe, K.: Patterns of circular transition: what is the circular economy maturity of Belgian ports? Sustainability **12**(21), 9269 (2020)
30. Stein, M., Acciaro, M.: Value creation through corporate sustainability in the port sector: A structured literature analysis. Sustainability **12**(14), 5504 (2020)
31. Balletto, G., Borruso, G., Mei, G., Milesi, A.: Strategic circular economy in construction: case study in Sardinia, Italy. J. Urban Planning Dev. **147**(4) (2021)

32. Balletto, G., Borruso, G., Mei, G.: Location theory and circular economy. Demolition, constructions and spatial organization of firms–an applied model to Sardinia Region. The case study of the New Cagliari Stadium. In: Gervasi O., Murgante B., Misra S., Rocha, A.M.A.C., e Garau C. (eds), Computational Science and Its Applications–ICCSA 2019: 19th International Conference, Part III 19, pp. 535–550, Saint Petersburg (2019)
33. Bird J.H.: Ports, then and later, In: Charlier J., (eds.), Ports et mers. Mélangers maritimistes offerts à André Vigarié, Paradigme, pp. 157–170, Caen (1986)
34. Borruso, G.: Port-City relationship in the era of hybridization. A development model. J – Reading – J. Res. Didactics Geogr. **11**(2), 125–137 (2022)
35. Weber, A.: Theory of industrial location. San José State University Department of Economics, San Jose, CA, USA (1909)
36. Rodrigue, J.P., Notteboom, T.: Foreland-based regionalization: integrating intermediate hubs with port hinterlands. Res. Transp. Econ. **27**(1), 19–29 (2010)
37. Borruso, G., et al.: Rail ports as nodal gateways in the sea–land connections and the challenges of sustainable globalized markets: the case of Adriafer and the port of Trieste. In: Gervasi O., Murgante B., Misra S., Rocha, A.M.A.C., e Garau C. (eds), Computational Science and Its Applications – ICCSA Workshops 2023, LNCS vol. 14110, pp. 425–441, Springer -Verlag, Berlin (2023). https://doi.org/10.1007/978-3-031-37123-3_30
38. Tadini, M., Borruso, G.: Sea-rail intermodal transport in Italian gateway ports: a sustainable solution? The examples of La Spezia and Trieste. In: Gervasi O., Murgante B., Misra S., Rocha, A.M.A.C., e Garau C. (eds), Computational Science and Its Applications – ICCSA Workshops 2022, LNCS 13381, Springer-Verlag, Berlin, pp. 156–172 (2022)
39. Balletto, G., Borruso, G., Mei, G., Milesi, A.: Economia circolare, gestione dei rifiuti da costruzione e demolizione e produzione di Aggregati Riciclati. Il progetto MEISAR–Un'applicazione alla Sardegna. Boll. dell'Associazione Italiana di Cartografia. **170**, 178–200 (2020)
40. Gallo, A.: The logistic carbon footprint: a dynamic calculation tool for an indicator of the sustainability of logistic processes with a case study on the Port of Trieste. In: Gervasi, O., Murgante, B., Misra, S., Ana, M.A., Rocha, C., Garau, C. (eds.) Computational Science and Its Applications – ICCSA 2022 Workshops: Malaga, Spain, July 4–7, 2022, Proceedings, Part V, pp. 109–123. Springer International Publishing, Cham (2022). https://doi.org/10.1007/978-3-031-10548-7_9



Investigating the Relationship Between Land Use and Wealth in Italian Provinces

Giuseppe Borruso[1(✉)], Andrea Gallo[1,3(✉)], Francesco Magris[1(✉)], and Nicola Pontarollo[2(✉)]

[1] University of Trieste, Via A.Valerio 4/1, 34127 Trieste (TS), Italy
{giuseppe.borruso,francesco.magris}@deams.units.it, andrea.gallo3@phd.units.it
[2] University of Brescia, Via S.Faustino 74/B (BS), 25122 Brescia, Italy
nicola.pontarollo@unibs.it
[3] Ca' Foscari Venezia University, Dorsoduro, 3246, 30124 Venezia, Italy

Abstract. Land consumption is a significant problem in all economies, as it is having a significant impact on the quality of the environment. These effects include soil sealing, increased hydrogeological hazards, diminished pollution and greenhouse gas sequestration, and intensified competition over land for human activities. This problem is closely related to the phenomena of urban and non-urban sprawl. In this study we delve into the growing problem of land consumption, investigating its correlation with economic development. Our analysis focuses on the Italian context, using provinces as an intermediate administrative scale, and analyzes the evolution of land consumption over the past two decades in relation to economic development (GDP). We use spatial analysis techniques and local indicators of spatial association (LISA) to investigate both local effects and spatial clustering. Over the years examined, distinct spatial patterns of land use proximity emerge, showing areas with pronounced land use dominance in nearby locations. The implications of these findings may be notable for policy makers at the local, regional and national levels as they guide land development strategies.

Keywords: Land Use · LISA Methods · Spatial Analysis · Land Consumption

1 Introduction

The paper delves into the intricate relationship between economic growth and environmental sustainability. The focus is settled on the interplay between economic prosperity, urban development, and land use in Italy's different provinces. Challenged by concerns about the finite nature of our planet's resources and the need for sustainable development, the study aims to comprehensively explore the connection between Gross Domestic Product (GDP) per capita and land use.

The accelerating pace of urbanization, a consequence of economic progress, significantly influences land use patterns. The central question guiding the research is if economic progress within provinces results in responsible land use or contributes to environmental degradation. Inspired by the framework of the Environmental Kuznets

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2024
O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 401–412, 2024.
https://doi.org/10.1007/978-3-031-65238-7_27

Curve (EKC), which posits a non-linear relationship between economic growth and environmental quality, the study unfolds in two phases [1, 2].

The first phase of this article involves presenting more discursive contents in which the analysis of theoretical literature is presented, investigating the relationship between land use and GDP per capita dynamics on a national scale [3]. In the second phase, the study investigates this specific relationship through geospatial analysis tools such as the local indicator of spatial association (LISA) and different thematic maps. The aim is to determine, on a national scale, the evolution and the complex set of relationships that result from the relationship between these two indicators.

Utilizing methods of geospatial analysis, the research seeks to understand the interaction between economic wealth and land use practices. By analyzing data from the 107 Italian provinces, the study aims to identify patterns, thresholds, and potential saturation effects in the relationship between GDP per capita and land consumption. The analysis not only contributes to scholarly discourse but also holds implications for urban policy-making and sustainable development strategies.

The study aspires to shed light on pathways aligning economic progress with responsible land use, envisioning a future where prosperity and ecological sustainability coexist [4–6]. In conclusion, the text emphasizes the importance of the research's implications for shaping a sustainable and balanced trajectory for economic development and land use in the examined Italian provinces.

2 Land Use Dynamics and the Relationship Between Wealth and Land Consumption

This paper highlights various factors influencing the relationship between environmental degradation and income levels, with a focus on the income elasticity of environmental quality demand. This factor suggests that people prioritize environmental quality once their standard of living reaches a certain threshold, leading to a shift from quantity-based exploitation of natural resources to a focus on quality [7, 8].

The paper then narrows its focus to specific strands within the broader EKC literature, particularly exploring the relationship between income levels and urban development. It references research analyzing land use at a territorial level, by applying different methodologies of analysis, it's possible to find several works focused on spatial econometrics techniques to evaluate the relationship between land use and GDP per capita, in the context of the Environmental Kuznets Curve hypothesis. These studies use different proxies to define environmental degradation [9–11], but it is a rather widespread tendency to use land consumption as an indicator of environmental degradation. Several studies have investigated the implications of land use on environmental sustainability and local communities [12], highlighting how land use contributes to biodiversity loss, soil erosion, increased greenhouse gas emissions, impaired air and water quality, and increased susceptibility to extreme events such as floods and droughts [13]. In addition, numerous researchers have tried to understand and explain the drivers of land use change. Among these causes, we can indeed see that urban expansion, intensive agriculture, industrialization, and infrastructure development [14, 15] represent some of the main drivers of transformation.

In the context of the paper's goals, the authors plan to investigate the relationship between income levels and land use in 107 Italian provinces. The overall aim is to contribute valuable insights to the understanding the implications for sustainable development policies. The paper underscores the need to strike a delicate balance between economic prosperity and environmental preservation, emphasizing the complexity of this relationship and the importance of innovative solutions and collaborative efforts for achieving long-term sustainability.

3 Data and Methods

3.1 Setting the Context

We can highlight the nature related to the dynamics of land consumption and particularly in the context of environmental changes and human pressures. Scholars have extensively explored the adverse impacts of land consumption, linking it to biodiversity loss, soil erosion, greenhouse gas emissions, compromised air and water quality, and heightened vulnerability to extreme events [16, 17].

Root causes of land consumption, such as urban sprawl, intensive agriculture, industrialization, and infrastructure development, have been thoroughly examined [18–20]. Strategies like comprehensive land use planning, effective policies, and sustainable resource management are deemed essential for countering land consumption and ensuring environmental protection. Innovative approaches, including sustainable urban planning, efficient agricultural practices, eco-friendly technologies, and public awareness campaigns, are explored in the scientific literature [21, 22].

The concept of land use, encompassing various functions and socio-economic purposes, is emphasized for its pivotal role in ecological consequences, including agricultural land depletion, increased vulnerability to flooding, biodiversity loss, and contributions to climate change [21]. The text provides alarming data on land consumption in Italy, with the Fig. 1 aimed at introducing the national study area, that reveal an increasing trend and a loss of 2.2 square meters of land every second, as presented in Fig. 2 reported by Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA).

The connection between land consumption and population dynamics is discussed, highlighting an increase in artificial surfaces even with stable or decreasing resident populations. Data demonstrates a substantial rise in land consumed per capita, indicating rapid land transformation in Italy [23, 24]. The country faces a significant challenge with the swift expansion of artificial land cover, surpassing the EU average, leading to the loss of natural or semi-natural land, particularly due to urban sprawl in regions like Lombardy, Veneto, and Campania [25].

Specific provinces, including Brescia, Rome, and Naples, experience notable spikes in land use. Exceptions like Trieste, Gorizia, and Ancona successfully implement soil restoration efforts. Densely populated areas witness substantial increases in consumed land, contributing to the loss of green spaces and rising temperatures. Buildings occupy a significant portion of consumed land, with over 310 square kilometers occupied by unused and degraded structures [23]. The overall message underscores the urgency of addressing land consumption in Italy to ensure sustainable development and environmental preservation.



Fig. 1. Italian Framework for regional and provincial territorial aggregation

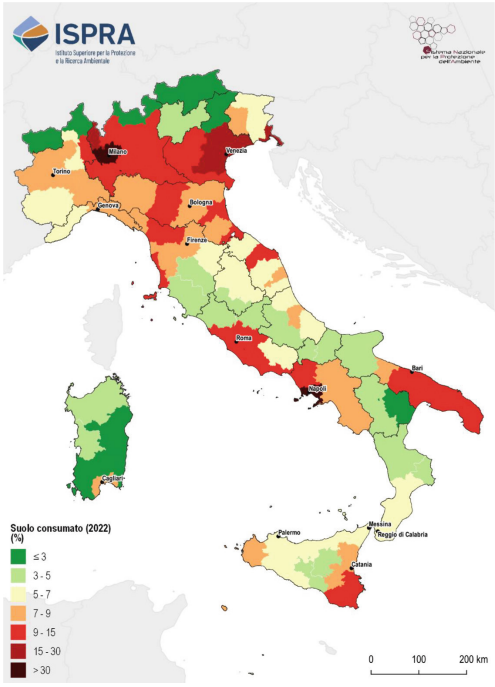


Fig. 2. Land Use consumption 2022 per provinces. Source: ISPRA – Istituto Superiore per la Protezione e la Ricerca

3.2 Methods

To understand the complex relationship between land consumption and wealth, the study considered the techniques of spatial autocorrelation, that can be considered as technique aimed at analyzing the spatial distribution of different elements while assessing the degree of influence and relationship with neighboring ones [26]. The Moran I (1948) index outlined by the following formula (1) is known as a global indicator of spatial autocorrelation and provides an indication of the presence of spatial autocorrelation.

$$I = \frac{N \sum_i \sum_j w_{ji}(x_i - \overline{x})(x_i - \overline{x})}{(\sum_i \sum_j w_{ji}) \sum_i (x_i - \overline{x})^2} \tag{1}$$

Instead, the specific location of high autocorrelation values is provided by the Local Indicators of Spatial Association (LISA) [27, 28]. One of the most widely used LISA indices is the one proposed by Anselin (1995) [30], which is regarded as a 'local' Moran indicator. We can also see, how the sum of all local Moran indices is equal to the Moran value.

Five cases can emerge, in which observations can be characterized by:

- High values of the phenomenon and high levels of similarity with the neighborhood (high-high), known as hot spots.
- Low values of the phenomenon and low levels of similarity with the neighborhood (low-low), known as cold spots.
- 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).
- Being completely devoid of significant autocorrelation.

The indicator is useful for assessing, for each spatial unit, the similarity between observations referring to a place in relation to adjacent elements [27]. The LISA indices provide an effective measure of the degree of relative spatial association between each spatial unit and its surrounding elements, allowing the type of spatial concentration to highlight spatial clusters related to a given phenomenon. This indicator has been widely used in the literature to capture the dynamics of spatial aggregation, and in particular, it has been applied to the analysis of urban sprawl on provincial and regional scales [28, 29].

3.3 Data Collection

The text focuses on understanding development dynamics in relation to the Kuznets environmental curve, analyzing land consumption across 107 Italian provinces from 2016 to 2021. The provinces are classified based on the NUTS 3 classification by Eurostat, with variations in provincial subdivisions in certain regions. The study highlights the diverse socio-cultural and economic aspects of the Italian territory, with Northern Italy characterized by industrial districts and higher per capita income compared to central and southern Italy. The geographical diversity of Italy is emphasized, with Northern Italy's

industrial focus and higher per capita income. The variables chosen for analysis provide insights into the relationship between land consumption, income, and urbanization. The study contributes to a nuanced understanding of development trajectories in different regions of Italy.

In particular, in this contribution, data on the percentage variation of land consumption per inhabitant for the 107 Italian provinces which can be found in the dataset provided by ISPRA, Istituto Superiore per la Protezione e la Ricerca Ambientale [30] and related to the logarithm of GDP per capita per province were taken into analysis, reported in euros at constant 2015 prices, with the GDP deflator taken from the World Bank, whose source is ISTAT [30], Istituto Nazionale di Statistica and the number of inhabitants per province was taken from Eurostat database.

These two different indicators were systematized through geo-spatial representation tools and in particular through the use of the Moran Index, in order to highlight the conjunctural trend of these two indicators in order to find whether there were common or inverse dynamics between land consumption and level of wealth.

4 Results and Discussion

To figure out the dynamics of development, we can observe that, post the 2008 economic crisis, the real estate sector witnessed a notable deceleration that has yet to fully recover. It peaked in 2006, experienced a decline until 2011, followed by a subsequent stagnation from 2011 to 2022 [32, 33]. Both private and public investments primarily targeted addressing housing needs, accompanied by a slowdown in the construction industry. This, along with a relatively steady population growth rate, created a situation where demand was saturated by existing built-up areas. These dynamics align strongly with expectations. Additionally, it is crucial to emphasize the trend of population concentration within specific urban centers. Particularly noteworthy is the ongoing urbanization shift towards the major urban centers in the Lombardy, Lazio, and Campania regions, significantly contributing to the expansion of Italian cities [34].

Hence, based on this analysis, we can infer a robust correlation between investment flows in the real estate sector and dynamics associated with land use. Consequently, the stagnant phase currently observed in Italy, characterized by limited economic growth, directly results in a restrained increase in land use. Conversely, an expansive period is linked to heightened construction activity for new residential, commercial, or industrial buildings, thereby escalating the demand for land in urban development and promoting the expansion of sealed soil.

To gain a deeper understanding of the evolving trend of land consumption at the provincial level, we employ the spatial distribution of land consumption and observe clustering phenomena, as depicted in Fig. 5. Moran's I the positive and statistically significant Moran's I suggests that areas with similar proportions of residential built-up land tend to be in close proximity. The increasing per capita land consumption share over the analyzed period indicates a growing trend of clustering, as illustrated in Fig. 4. Moreover, the rising Gini Coefficient, acting as a measure of spatial inequality in this context, aligns with Moran's I, affirming the inclination towards polarization. However, it is noteworthy that the obtained results align with the findings presented by Bimonte and Stabile (2017) [9], who utilized building permits as a proxy for land consumption.

The cluster analysis carried out through Moran's I regarding the level of GDP per capita, presented in Fig. 3 shows an extremely unequal distribution of income between the north and south of the national context. In particular, this methodology allows us to put in evidence how there is a clear territorial discontinuity regarding the distribution of wealth per capita. By highlighting results similar to those found in literature [35, 36], we can in fact observe how this index is able to photograph the different spatial distribution of income on a national scale, observing an extremely sensitive distinction between the north and south of the country, with an insignificant band represented by central Italy [37].

Income inequality on a national scale represents not only an economic problem, but also an important social problem [38]. Economic instability and low job prospects are an important driver for the internal mobility of young people who annually choose to migrate from southern or island areas of Italy to northern regions for work or study.

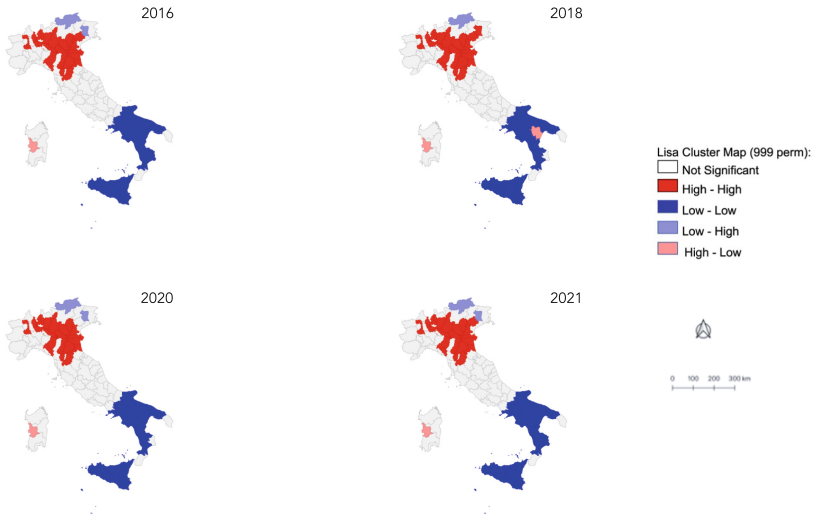


Fig. 3. Moran Index cluster map for the logarithm of the GDP per capita for years 2016, 2018, 2020, 2021

On the other hand, as far as the percentage change in per capita land consumption is concerned, we can see that there is a constant trend between 2016 and 2020, in which several provinces in southern Italy are involved, with particular reference to Puglia, Campania and Sicily, clearly observable in Figs. 4 and 5. We must also note how this dynamic tends to reverse in 2021, where we can see that there is an extremely significant cluster regarding an area covering the Italian regions of northern Emilia-Romagna, Veneto, and eastern Lombardy.

This significant increase in land consumption in 2021 may find reason to be related to the economic recovery that occurred following the global Covid-19 pandemic and the start of the nationwide economic recovery plan. The previous five-year period, on the other hand, was strongly characterized by a multitude of investments in infrastructure

spending by the Italian government, aimed at reducing the economic gap between the north and south of the country. With this in mind, we can note, how in particular the National Operational Plan (NOP 2014–2020) [39] has allocated substantial resources to try to improve the productive economic fabric of Southern Italy: this could be one of the causes to which we can attribute an extremely relevant soil increase for the previously mentioned areas.

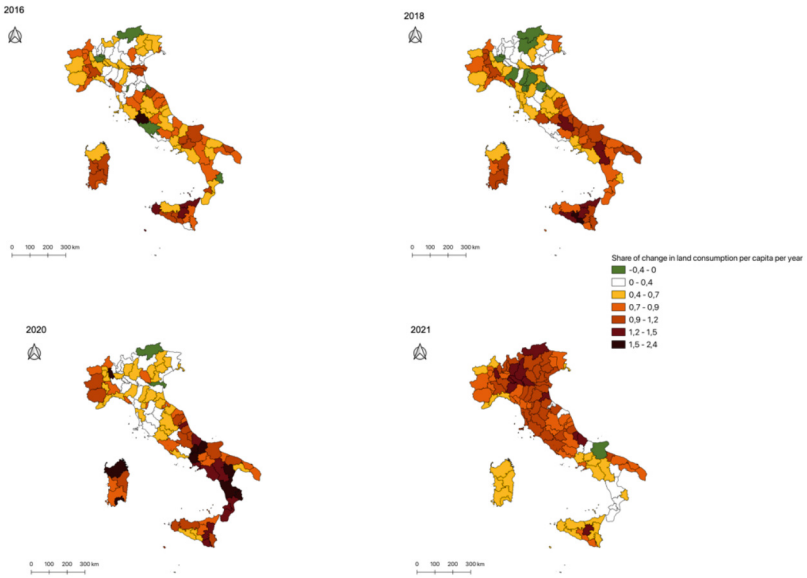


Fig. 4. Share of change in land consumption per capita year 2016, 2018, 2020, 2021 Source: Author's elaboration on data ISPRA

Bringing together the results of the spatial analysis regarding the distribution of GDP and land consumption, it becomes clear that there is an inverse relationship between these two indicators. This relationship is also highlighted in the graphs presented in Fig. 6.

The distribution of economic well-being is strongly polarized between the more prosperous northern Italy, due in part to the widespread presence of a better industrial and infrastructural fabric, while southern Italy is economically more underdeveloped. Conversely, with regard to the variation in land consumption, we can observe that it is precisely southern Italy that is subject to more relevant systemic pushes and significantly increases the amount of land consumed in the five-year period 2016–2021. This leads us to conclude that there might be an inverse relationship between land consumption and GDP per capita, where it must be pointed out, however, that in the face of an observable trend between 2016 and 2020, the year 2021 represents a turnaround from the previous data analyzed.

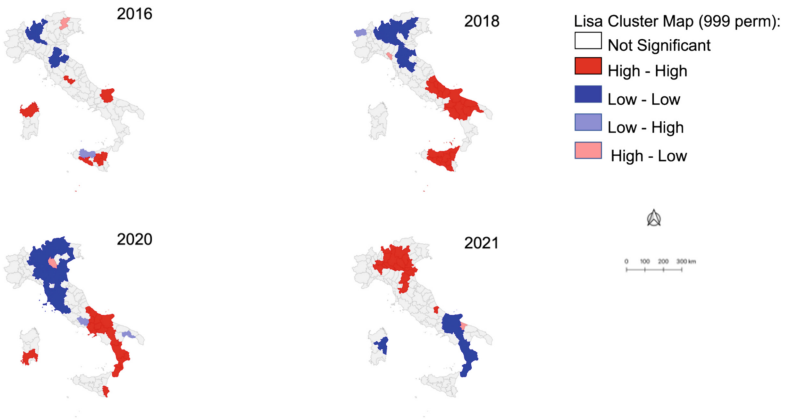


Fig. 5. Moran Index cluster map for the share of change of land use per capita year 2016, 2018, 2020, 2021

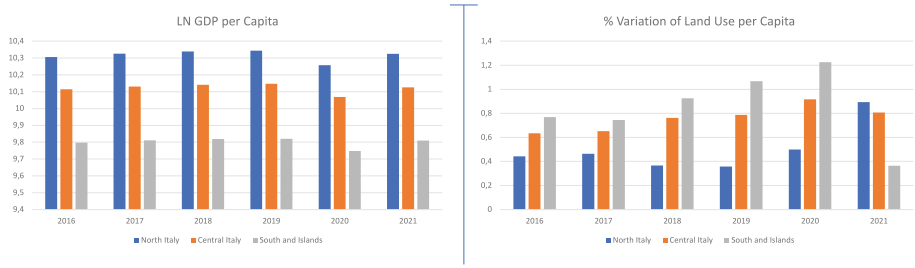


Fig. 6. Graphs of the trend of the log of the GDP per capita and the % change in Land Use per capita

5 Conclusions

This paper conducts an empirical analysis of the relationship between GDP per capita and land consumption in the Italian NUTS 3 provincial context, focusing on the unexplored area of provincial-level land use. The study identifies a clear convex relationship between land consumption and economic development, suggesting a clustering tendency towards major urban and suburban centers, reflecting metropolitan expansion and agglomeration around production districts. The choice to use land use as a proxy for environmental degradation stems from its environmental and social implications, contributing to biodiversity loss, greenhouse gas emissions, and societal dynamics related to urban agglomeration.

The spatial analysis catches the impact of land use change's interaction with neighboring provinces, emphasizing the regional and provincial dependence on socio-economic dynamics. From the spatial analysis we can see that there is a relationship between income per capita and land consumption, and in particular we can see that on a certain level of spatial distribution, beyond a certain income, environmental preservation gives way to land development, prioritizing private gains over societal costs. This finding

aligns with other studies on land degradation in Italy, pointing to economic, social, and political factors driving the construction and real estate sector at the expense of broader social interests.

In conclusion, the study challenges the assumption that achieving sustainable development is an automatic process, emphasizing the need to move beyond market-based economics toward political and social considerations. The results underscore the complex interplay of economic, social, and political factors influencing environmental outcomes.

Acknowledgments. Conceptualization, methodology, formal analysis, materials and resources, software and data curation: all authors. Validation: all authors. In particular: Magris and Pontarollo wrote Sect. 1, Gallo wrote Sect. 2, 3.1, 4; Borruso wrote Sect. 3.2; Borruso and Gallo wrote Sect. 3.3; all the authors wrote Sect. 5.

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

References

1. Ayres, R.U.: Resources, environment, and economics: Applications of the materials/energy balance principle. Wiley, United States (1978)
2. Kuznets, S.: Economic growth and income inequality. Am. Econ. Rev. **49**, 1–28 (1955)
3. Dinda, S.: Environmental Kuznets curve hypothesis: a survey. Ecol. Econ. **49**(4), 431–455 (2004)
4. Gill, A.R., Viswanathan, K.K., Hassan, S.: A test of environmental Kuznets curve (EKC) for carbon emission and potential of renewable energy to reduce green house gases (GHG) in Malaysia. Environ. Dev. Sustain. **20**, 1103–1114 (2018)
5. Grossman, G.M., Krueger, A.B.: Environmental impacts of a North American free trade agreement (1991)
6. Stern, D.I.: Progress on the environmental Kuznets curve? Environ. Dev. Econ. **3**(2), 173–196 (1998)
7. Barbier, E.B.: Introduction to the environmental Kuznets curve special issue. Environ. Dev. Econ. **2**(4), 369–381 (1997)
8. Mrabet, Z., Alsamara, M.: Testing the Kuznets Curve hypothesis for Qatar: a comparison between carbon dioxide and ecological footprint. Renew. Sustain. Energy Rev. **70**, 1366–1375 (2017)
9. Bimonte, S., Stabile, A.: Land consumption and income in Italy: a case of inverted EKC. Ecol. Econ. **131**, 36–43 (2017)
10. Bimonte, S., Stabile, A.: The effect of growth and corruption on soil sealing in Italy: a regional environmental Kuznets Curve analysis. Environ. Resource Econ. **74**, 1497–1518 (2019)
11. Pontarollo, N., Serpieri, C.: Testing the environmental Kuznets Curve hypothesis on land use: the case of Romania. Land Use Policy **97**, 104695 (2020)
12. Marsh, W.M., Grossa, J., Jr.: Environmental geography: science, land use, and earth systems. John Wiley and Sons, New York (1996)
13. Turner, W.R.: Citywide biological monitoring as a tool for ecology and conservation in urban landscapes: the case of the Tucson Bird Count. Landsc. Urban Plan. **65**(3), 149–166 (2003)
14. Walker, B., Salt, D.: Resilience thinking: sustaining ecosystems and people in a changing world. Island press, Washington (2012)

15. Meerow, S., Newell, J.P., Stults, M.: Defining urban resilience: A review. Landscape Urban Planning **147**, 38–49 (2016). https://doi.org/10.1016/j.landurbplan.2015.11.011
16. Janssen, M. A.: An update on the scholarly networks on resilience, vulnerability, and adaptation within the human dimensions of global environmental change. Ecol. Soc. **12**(2) (2007)
17. Maddison, D.: Environmental Kuznets curves: a spatial econometric approach. J. Environ. Econ. Manag. **51**(2), 218–230 (2006)
18. Amato, F., Maimone, B.A., Martellozzo, F., Nolè, G., Murgante, B.: The effects of urban policies on the development of urban areas. Sustainability **8**(4), 297 (2016)
19. Bencardino, M.: Land take and urban sprawl: drivers e contrasting policies. Boll. della Società Geografica Italiana **8**(2), 217–237 (2015)
20. Bencardino, M.: An estimate of land take in municipal planning of the Campania Region. In: Gervasi, O., et al. (eds.) ICCSA 2017. LNCS, vol. 10408, pp. 73–88. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-62404-4_6
21. Turner, N.J., Davidson-Hunt, I.J., O'flaherty, M.: Living on the edge: ecological and cultural edges as sources of diversity for social—ecological resilience. Hum. Ecol. **31**, 439–461 (2003)
22. Hassan, Z., et al.: Dynamics of land use and land cover change (LULCC) using geospatial techniques: a case study of Islamabad Pakistan. Springerplus **5**, 1–11 (2016)
23. Sistema Nazionale per la Protezione dell'Ambiente (SNPA), Consumo di suolo e servizi ecosistemici. Edizione 2022. Report tecnico SNPA (2022)
24. Gallo, A., De Simone, C.S.: Agrovoltaic as an answer to the difficult relationship between land use and photovoltaics. a case study from Apulia Region. In: Gervasi O., Murgante B., Misra S., Rocha. A.M.A.C. Garau C. (eds), Computational Science and Its Applications – ICCSA Workshops 2023, LNCS vol. 14110, pp. 547–559, Springer-Verlag, Berlin (2023). https://doi.org/10.1007/978-3-031-37114-1_38
25. Iodice, S., Garbarino, E., Cerreta, M., Tonini, D.: Sustainability assessment of construction and demolition waste management applied to an Italian case. Waste Manage. **128**, 83–98 (2021)
26. Balletto, G., Sinatra, M., Milesi, A., Ghiani, E., Borruso, G.: A conceptual framework to correlate the electric transition and well-being and equity. The Italy case. In: Gervasi O., Murgante B., Misra S. Garau C. (eds), Computational Science and Its Applications – ICCSA Workshops 2023, LNCS vol. 14112, pp. 66–80, Springer-Verlag, Berlin (2023). https://doi.org/10.1007/978-3-031-37120-2_5
27. Murgante, B., Borruso, G.: Analyzing migration phenomena with spatial autocorrelation techniques. In: Murgante, B., Gervasi, O., Misra, S., Nedjah, N., Rocha, A.M.A.C., Taniar, D., Apduhan, B.O. (eds.) ICCSA 2012. LNCS, vol. 7334, pp. 670–685. Springer, Heidelberg (2012). https://doi.org/10.1007/978-3-642-31075-1_50
28. Balletto, G., Mundula, L., Milesi, A., Ladu, M.: Cohesion policies in Italian metropolitan cities. Evaluation and challenges. In: Gervasi, O., Murgante, B., Misra, S., Garau, C., Blečić, I., Taniar, D., Apduhan, B.O., Rocha, A.M.A.C., Tarantino, E., Torre, C.M., Karaca, Y. (eds.) ICCSA 2020. LNCS, vol. 12255, pp. 441–455. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-58820-5_33
29. Balletto, G., Sinatra, M., Sinatra, F., Borruso, G.: Industrial Symbiosis and Circular Urban Practices. In: Marucci A., Zullo F., Fiorini L., Saganeiti L. (eds), Lecture Notes in Civil Engineering, Proceeding of International Conference on Innovation in Urban and Regional Planning (INPUT), Volume 2, pp. 14–24, Cham: Springer Nature Switzerland (2023). https://doi.org/10.1007/978-3-031-54096-7_2
30. https://www.isprambiente.gov.it/it/attivita/suolo-e-territorio/suolo/il-consumo-di-suolo/i-dati-sul-consumo-di-suolo .Access 13 Jan (2023)
31. Anselin, L.: Local indicators of spatial association—LISA. Geogr. Anal. **27**(2), 93–115 (1995)

32. Belotti, E.: The invisible hand of the shareholding state: the financialization of Italian real-estate investment funds for social housing. Hous. Stud. **38**(7), 1260–1283 (2023)
33. Storm, S.: Lost in deflation: Why Italy's woes are a warning to the whole Eurozone. Int. J. Polit. Econ. **48**(3), 195–237 (2019)
34. Gavinelli, D., Molinari, P.: Il Piemonte nordorientale: area "cerniera" o piattaforma territoriale nel sistema urbano europeo? Rivista Geografica Italiana **122**(4), 489–502 (2015)
35. Impicciatore, R., Tosi, F.: Student mobility in Italy: the increasing role of family background during the expansion of higher education supply. Res. Soc. Stratification Mobility **62**, 100409 (2019)
36. Cannari, L., Gambacorta, R., D'Alessio, G.: Capital gains and wealth distribution in Italy. SSRN Electron. J. (2008). https://doi.org/10.2139/ssrn.1182603
37. Salvati, L., Zitti, M., Carlucci, M.: Territorial systems, regional disparities and sustainability: Economic structure and soil degradation in Italy. Sustainability **6**(5), 3086–3104 (2014)
38. Enea, M.: From South to North? Mobility of Southern Italian students at the transition from the first to the second level university degree. In: Studies in Theoretical and Applied Statistics: SIS 2016, pp. 239–249. Springer International Publishing, Salerno, Italy (2018). https://doi.org/10.1007/978-3-319-73906-9_22
39. https://ponir.mit.gov.it/#:~:text=Il%20PON%20Infrastrutture%20e%20Reti,l%27ambiente%20e%20il%20territorio. Access 29 Jan 2024

Author Index

A
Annunziata, Alfonso 202, 218
Anselmi, Chiara 61

B
Balletto, Ginevra 131, 159, 384
Bollini, Letizia 3
Borruso, Giuseppe 131, 159, 369, 384, 401
Bratchikov, Denis 334

C
Citterio, Beatrice 3
Cutini, Valerio 61

D
Derevschikov, Vladimir 290
Deri, Federica 61
Di Dato, Chiara 18
Di Ruocco, Irina 77
Dore, Salvatore 384

F
Fečko, Miroslav 112
Fenu, Nicolò 131
Fusco, Giovanni 50

G
Gadylshin, Kirill 263, 276, 352
Gadylshina, Kseniia 276
Gagliano, Filippo 141
Gallo, Andrea 384, 401
Giuffrida, Salvatore 141
Gonchar, Alexandra 290
Gondyul, Elena 263, 352

K
Khachkova, Tatyana 250, 290

L
Leone, Antonio 32
Lisitsa, Vadim 237, 250, 263, 276, 290, 305, 352

M
Magris, Francesco 401
Mara, Federico 61
Mazzarelli, Giovanni 202
Mital', Ondrej 112
Murgante, Beniamino 77, 202, 218

N
Nasca, Ludovica 141
Nicolaides, Chrysses 93
Novikov, Mikhail 237, 321

P
Perez, Joan 50
Pontarollo, Nicola 401
Poplin, Alenka 189
Primiceri, Sandra 369
Prokhorov, Dmitry 290, 334

R
Reshetova, Galina 321, 334
Ripa, Maria Nicolina 32
Romenski, Evgeniy 237, 321
Ručinská, Silvia 112

S
Sinatra, Francesca 369, 384
Solovyev, Sergey 305
Stratigea, Anastasia 93

© The Editor(s) (if applicable) and The Author(s), under exclusive license
to Springer Nature Switzerland AG 2024

O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14817, pp. 413–414, 2024.
https://doi.org/10.1007/978-3-031-65238-7

T
Theodora, Yiota 93
Trovato, Maria Rosa 141

V
van der Laag Yamu, Claudia Hedwig 202
Ventura, Vittoria 141
Vishnevsky, Dmitry 263, 276, 352
Vomero, Michele 32

Z
Živković, Ljiljana 172