Osvaldo Gervasi · Beniamino Murgante ·
Chiara Garau · Ana Maria A. C. Rocha ·
M. Noelia Faginas Lago · Ana C. Braga ·
Yeliz Karaca (Eds.)

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Computational Science and Its Applications – ICCSA 2026 Workshops

Braga, Portugal, June 30 – July 3, 2026
Proceedings, Part VIII

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Editors

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Editors
Osvaldo Gervasi
University of Perugia
Perugia, Perugia, Italy

Chiara Garau
University of Cagliari
Cagliari, Italy

M. Noelia Faginas Lago
University of Perugia
Perugia, Italy

Yeliz Karaca
University of Massachusetts
Worcester, MA, USA

Beniamino Murgante
University of Basilicata
Potenza, Italy

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

Ana C. Braga
University of Minho
Braga, Portugal

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Preface

These 9 volumes (LNCS volumes 16758–16766) comprise the peer-reviewed papers from the 57 Workshops of the 2026 International Conference on Computational Science and Its Applications (ICCSA 2026), held between June 30 and July 3, 2026, in Braga, Portugal. The peer-reviewed papers from the six main conference tracks are published in a separate set of 3 volumes (LNCS volumes 16767–16769).

The conference was held in a hybrid format, with the vast majority of participants attending in person, hosted by the University of Minho in Braga, Portugal.

We enabled virtual participation for those who did not attend the event in person due to logistical, political, or economic constraints by adopting a technological infrastructure based on open-source software (Jitsi + Riot) and a commercial Cloud infrastructure. ICCSA 2026 was organized by the University of Minho (Portugal), the University of Perugia (Italy), the University of Basilicata (Italy), the University of Cagliari (Italy), Monash University (Australia), and Kyushu Sangyo University (Japan).

With the 2026 edition, ICCSA celebrated its 26th anniversary, marking a new chapter in its longstanding history after its memorable 25th anniversary celebrated in Istanbul, Türkiye. Hosted in Braga, Portugal, the conference found a particularly meaningful setting in one of Europe's oldest and most vibrant academic cities, a place where historical depth, cultural continuity, and contemporary scientific exchange meet. Braga offers an inspiring European context for renewing the international and intercultural dialogue that has always characterized ICCSA, while giving new visibility to the role of computational science in addressing the complex challenges of cities, territories, technologies, and societies.

ICCSA 2026 marked another fruitful and thought-provoking academic event in the International Conference on Computational Science and Its Applications (ICCSA) conference series, previously held in Istanbul, Türkiye (2025), Hanoi, Vietnam (2024), Athens, Greece (2023), Málaga, Spain (2022), Cagliari, Italy (hybrid with few participants in presence in 2021 and completely online in 2020), Saint Petersburg, Russia (2019), Melbourne, Australia (2018), Trieste, Italy (2017), Beijing, China (2016), Banff, Canada (2015), Guimarães, 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 constitutes the main pillar of most present research, industrial, and commercial applications, and plays a unique role in exploiting innovative ICT technologies, and the ICCSA conference series has, accordingly, provided ample opportunities 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 large language models, machine learning, and Artificial Intelligence,

and their applications across the most diverse technological, economic, and industrial fields, amongst others.

The ICCSA 2026 conference included 57 workshops, focusing on topical issues of utmost importance to science, technology, and society: from new computational approaches for earth science, to mathematical methods for image processing, new statistical and optimisation methods, several Artificial Intelligence approaches, sustainability issues, smart cities and related technologies, to name a few. In addition, ICCSA 2026 included six general tracks covering computational science and its applications: Computational Methods, Algorithms and Scientific Applications; High-Performance Computing and Networks; Geometric Modelling, Graphics and Visualisation; Advanced and Emerging Applications; Information Systems and Technologies; and Urban and Regional Planning.

For these Workshops Proceedings, we accepted 328 full papers, 23 short papers, and 3 Ph.D. Showcase papers from a total of 1184 submissions (acceptance rate 29.9%). Reviews were single blind, and submissions received 2.6 reviews each, on average. In the Main Conference Proceedings, we accepted 119 full papers, 3 short papers, and 2 Ph.D. Showcase papers from 431 submissions to the General Tracks of the Conference (acceptance rate of 29.9%). We would like to convey our sincere appreciation to the workshop chairs and co-chairs and program committee members, for their diligent work, commitment, and dedication.

The success and consistent maintenance of the ICCSA conference series in general, and of ICCSA 2026 in particular, rely upon 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 other individuals in various roles. Thus, we take this opportunity to wholeheartedly thank each and every one.

We also wish to thank the publisher, Springer, for accepting the proceedings, and for their kind assistance and cooperation during the editing process. We would cordially like to invite you to refer to the ICCSA website https://iccsa.org, where you can find the relevant details regarding this academic endeavour and our event.

June 2026

Chiara Garau
Ana Maria A. C. Rocha
Osvaldo Gervasi
Beniamino Murgante

Welcome Message from the Organizers

On behalf of the Local Organizing Committee of ICCSA 2026, it is our great pleasure to welcome you to the 26th International Conference on Computational Science and Its Applications, held from June 30 to July 3, 2026, at the University of Minho in Braga, Portugal.

We are deeply honoured by the trust placed in us by the ICCSA General Chairs in organizing another edition of this successful conference series. We hope that ICCSA 2026 provided an inspiring environment for scientific exchange, collaboration, and discussion among researchers from all over the world.

The conference took place at the University of Minho, one of the most prestigious higher education institutions in Portugal. Founded in 1973, the University of Minho has campuses in Braga and Guimaraes and is widely recognized for its academic excellence, research activity, and strong international outlook.

Braga, one of the oldest cities in Portugal, is renowned for its historical heritage, cultural vitality, and welcoming atmosphere.

Located in the heart of the Minho region, the city combines tradition with modernity, offering visitors renowned gastronomy, beautiful landscapes, and the unique character of *Vinho Verde* wine.

The scientific program of ICCSA 2026 included plenary lectures delivered by distinguished scientists, together with a broad range of workshops covering several areas of Computational Science and its Applications. We believe that the conference provided excellent opportunities to share ideas, discuss emerging challenges, and foster new collaborations.

In addition to the scientific sessions, participants had the opportunity to enjoy a rich social program.

Planned activities included a Welcome Reception at Largo do Paço, the Rectorate of the University of Minho, located in the former Archbishop's Palace - one of the most emblematic historical buildings in the city center; a *Vinho Verde* wine-tasting experience at Quinta d'Amares, where particiapnts could discover the art of winemaking; and a guided visit to the coastal city of Viana do Castelo, renowned for its maritime heritage, traditional architecture, and beautiful Atlantic scenery. The conference gala dinner took place at Colunata Eventos, located within the Bom Jesus do Monte sanctuary, a UNESCO World Heritage Site, where ICCSA participants enjoyed delicious recipes and a wonderful view over the city of Braga.

The success of ICCSA 2026 would not have been possible without the dedication and enthusiasm of many collaborators and volunteers, whose hard work and commitment greatly contributed to the organization of the conference.

On behalf of the Local Organizing Committee, it was our honour to warmly welcome you to the beautiful city of Braga and we hope you had an enjoyable and productive conference.

We enjoyed meeting you in Braga.

Sincerely yours,

On behalf of the Local Organizing Committee.

June 2026 Ana Maria A. C. Rocha

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Computational methods for Porous materials (CompPor 2026)

Workshop Organizers

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Evgeniy Romenski	Sobolev Institute of Mathematics, Russia

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Sergey Solovyev	Sobolev Institute of Mathematics SB RAS, Russia
Vladimir Cheverda	Sobolev Institute of Mathematics SB RAS, Russia

Workshop on Computational Science and HPC (CSHPC 2026)

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Robert Makin	Western Michigan University, USA

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Keigo Nitadori	RIKEN, Japan
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Shigeyoshi Aoyama	KEK, Japan
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Cities, Technologies and Planning (CTP 2026)

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Malgorzata Hanzl	Lodz University of Technology, Poland
Anastasia Stratigea	National Technical University of Athens, Greece
Ljiljana Zivkovic	Republic Geodetic Authority, Serbia
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Clara Di Fazio	University of Trieste, Italy
Andrea Gallo	Università degli Studi di Trieste, Italy
Francesca Sinatra	University of Trieste, Italy

Evaluating Inner Areas Potentials (EIAP 2026)

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Beatrice Mecca	Politecnico di Torino, Italy

sustainablE mobiLity and Last mIle lOgisTic in urban context (ELLIOT 2026)

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Econometrics and Multidimensional Evaluation in Urban Environment (EMEUE 2026)

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Sabrina Sacco	University of Naples Federico II, Italy

Ecosystem Services in Spacial Planning for climate neutral urban and rural areas (ESSP 2026)

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Federica Leone	University of Cagliari, Italy
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The 16th International Workshop on Future Information System Technologies and Applications (FiSTA 2026)

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Toshihiro Yamauchi	Okayama University, Japan
Toshihiro Uchibayashi	Kyushu University, Japan
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Geographical Analysis, Urban Modeling, Spatial Statistics (Geog-And-Mod 2026)

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Generative and Neuro-Symbolic Artificial Intelligence for Real-World Systems (GNS-AI 2026)

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Manuel Rodrigues	University of Minho, Portugal
Regina Sousa	University of Minho, Portugal

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Geomatics for Resource Monitoring and Management (GRMM 2026)

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International Workshop on Information and Knowledge in the Internet of Things (IKIT 2026)

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Intelligent Sustainable Development: from Models to Real-World Impact (ISD 2026)

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Eduardo Bezerra	Federal Center for Technological Education of Rio de Janeiro, Brazil
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Multidimensional Evolutionary Evaluations for Transformative Approaches (MEETA 2026)

Workshop Organizers

Maria Cerreta	University of Naples Federico II, Italy
Giuliano Poli	Università Federico II di Napoli, Italy
Gaia Daldanise	CNR Institute for Research on Innovation and Services for Development, Italy
Ludovica La Rocca	University of Federico II of Naples, Italy
Maria Somma	University of Naples Federico II, Italy
Sabrina Sacco	University of Naples Federico II, Italy

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Chiara Mazzarella	TUDelft, The Netherlands
Simona Panaro	University of Sussex Business School, UK
Eugenio Muccio	University of Naples Federico II, Italy

Building multi-dimensional Models for assessing complex Environmental Systems (MES 2026)

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Vanessa Assumma	University of Bologna, Italy
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Giulia Datola	Politecnico di Milano, Italy
Federico DellAnna	Politecnico di Torino, Italy
Marta Dell'Ovo	Politecnico di Milano, Italy
Marco Rossitti	Politecnico di Milano, Italy

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Sebastiano Barbieri	Politecnico di Torino, Italy
Giulio Cavana	Politecnico di Torino, Italy
Marta Bottero	Politecnico di Torino, Italy
Francesca Torrieri	Politecnico di Milano, Italy
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Giorgia Sugoni	Links Foundation, Italy
Lucia Petronio	University of Bologna, Italy
Marco Alvise Bragadin	University of Bologna, Italy

Computational Mechanics, Intelligence, and Data (MIND 2026)

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Renato Zona	Università della Campania Vanvitelli, Italy

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Ali Forooghi	University of Campania Luigi Vanvitelli, Italy
Mario Argenziano	University of Palermo, Italy
Donato Perfetto	University of Campania Luigi Vanvitelli, Italy

Modelling Liveable Cities: Techniques, Methods, Challenges, and Perspectives Behind the X-Minute City (MLC 2026)

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Valerio Cutini	University of Pisa, Italy

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Chiara Di Dato	University of L Aquila, Italy
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Chiara Anselmi	University of Pisa, Italy

Mathematical Methods for Image Processing and Understanding 2026 (MMIPU 2026)

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Simone Rebegoldi	University of Modena and Reggio Emilia, Italy
Valentina Giorgetti	Università degli Studi di Perugia, Italy
Vita Leonessa	University of Basilicata, Italy

MOdels and indicators for assessing and measuring the urban settlement deVElopment in the view of NET ZERO by 2050 (MOVEto0 2026)

Workshop Organizers

Lorena Fiorini	University of L'Aquila, Italy
Lucia Saganeiti	Institute of Methodologies for Environmental Analysis (IMAA) CNR, Italy
Angela Pilogallo	Institute of Methodologies for Environmental Analysis (IMAA) CNR, Italy

Francesco Zullo	University of L'Aquila, Italy
Alessandro Marucci	University of L'Aquila, Italy

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Giuseppe Borruso	University of Trieste, Italy
Chiara Garau	University of Cagliari, Italy
Beniamino Murgante	University of Basilicata, Italy
Ljiljana Zivkovic	Republic Geodetic Authority, Serbia
Luigi Santopietro	Institute of Methodologies for Environmental Analysis National Research Council of Italy CNR IMAA, Italy
Ilaria Delponte	University of Genoa, Italy
Carmen Guida	Università degli Studi di Napoli Federico II, Italy
Chiara Di Dato	University of L'Aquila, Italy

Numerical Aspects in Machine Learning For Dynamical Systems (NAMLYS 2026)

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Livia Marcellino	University of Naples Parthenope, Italy
Valeria Mele	University of Naples Federico II, Italy

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Marco Lettiero	University of Naples Parthenope, Italy
Francesco Peluso	University of Naples Parthenope, Italy

Numerical Methods and Machine Learning in Science & Engineering (NMLSE 2026)

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Luís Ferrás	University of Minho, Portugal
Eliana Costa e Silva	Polytechnic of Porto, Portugal

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Bruno Veloso	Universidade do Porto, Portugal
Luís Louro	University of Minho, Portugal
Weronika Wojtak	CCG/ZGDV Institute, Portugal
Wolfram Erlhagen	University of Minho, Portugal

6th Workshop on Privacy in the Cloud/Edge/IoT World 2026 (PCEIoT 2026)

Workshop Organizers

Lelio Campanile	Università degli Studi della Campania Luigi Vanvitelli, Italy
Mauro Iacono	Università degli Studi della Campania Luigi Vanvitelli, Italy
Michele Mastroianni	University of Foggia, Italy

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Gianni D'Angelo	University of Salerno, Italy
Biagio Boi	University of Salerno, Italy
Luigi Piero Di Bonito	Università degli Studi della Campania, Italy

Preserving Our Past: Spatial and Remote Sensing Technologies for Cultural Heritage in a Changing Climate (POP 2026)

Workshop Organizers

Maria Danese	Institute of Heritage Science of the National Research Council of Italy (CNR ISPC), Italy
Rosa Lasaponara	Institute of Methodologies for Environmental Analysis (CNR IMAA), Italy
Nicola Masini	Institute of Heritage Science of the National Research Council of Italy (CNR ISPC), Italy

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Dario Gioia	Institute of Heritage Science of the National Research Council of Italy (CNR ISPC), Italy
Marilisa Biscione	Institute of Heritage Science of the National Research Council of Italy (CNR ISPC), Italy
Valentina Florio	CNR, Italy
Antonio Minervino Amodio	Institute of Heritage Science of the National Research Council of Italy (CNR ISPC), Italy

Scientific Computing Infrastructure (SCI 2026)

Workshop Organizers

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Elena Stankova	Saint Petersburg State University, Russia

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Suren Abrahamyan	Institute for Informatics and Automation Problems of NAS RA, Armenia
Ashot Gevorkyan	Institute for Informatics and Automation Problems NAS of Armenia, Armenia

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Alexander Bogdanov	St. Petersburg State University, Russia
Nataliia Kulabukhova	AutoTech, Russia
Alexander Degtyarev	St.Petersburg State University, Russia
Alexander Bogdanov	St. Petersburg State University, Russia

Socio-Economic and Environmental Models for Land Use Management (SEMLUM 2026)

Workshop Organizers

Debora Anelli	Sapienza University of Rome, Italy
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Francesco Tajani	Sapienza University of Rome, Italy
Felicia Di Liddo	Polytechnic University of Bari, Italy

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Antonella Roma	Sapienza University of Rome, Italy
Francesca Fariello	Sapienza University of Rome, Italy

Ports and logistics of the future - Smartness and Sustainability (SmartPorts 2026)

Workshop Organizers

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Gianfranco Fancello	University of Cagliari, Italy
Veronica Camerada	Università degli studi di Sassari, Italy
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Mara Ladu	University of Cagliari, Italy
Ginevra Balletto	University of Cagliari, Italy
Francesca Sinatra	University of Trieste, Italy

Sustainable evolution of long-Distance frEight and paSsenger Transport (SOLIDEST 2026)

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Vita Leonessa	University of Basilicata, Italy
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Vadim Lisitsa	Institute of Petroleum Geology and Geophysics SB RAS, Russia
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Humberto Rocha	University of Coimbra, Portugal
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Matteo Sacchet	University of Turin, Italy
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Lucia Saganeiti	Institute of Methodologies for Environmental Analysis, National Research Council, Italy
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Adriano Silva	Instituto Politecnico de Bragança, Portugal
Angela Silva	Universidade do Minho, Portugal

Paula Simões	Military Academy, Portuguese Army, Portugal
Francesca Sinatra	University of Trieste, Italy
Mercedes Solla	Universidade de Vigo, Spain
Sergey Solovyev	Sobolev Institute of Mathematics SB RAS, Russia
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Federica Sortino	Università degli Studi di Enna Kore, Italy
Eleonora Sottile	University of Cagliari, Italy
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Isidora Đurić	University of Novi Sad, Serbia

Plenary Lectures

Digital Twins for Cities – The Rise of the Socio-Technical System

Claudia van der Laag

Department of Built Environment, Oslo Metropolitan University, Norway

Abstract. Cities are entering a new era in which digital twins are no longer simply technical replicas of urban systems, but evolving socio-technical infrastructures that shape how cities are planned, governed, and experienced. Across the world, urban digital twins are being adopted to address some of the most pressing challenges of our time — climate adaptation, urban resilience, mobility transitions, decarbonisation, infrastructure management, and inclusive governance. Yet as these technologies become increasingly sophisticated, a fundamental question emerges: can digital twins truly support more democratic and human-centred cities, or will they reinforce existing structures of power and expertise? In this keynote, Claudia van der Laag explores the transformation of urban digital twins from data-driven modelling tools into collaborative platforms for urban decision-making and societal change. It argues that the future of digital twins lies not only in advances in artificial intelligence, real-time data integration, simulation, and predictive analytics, but equally in the ability to connect technological innovation with governance, participation, and human agency. Drawing on emerging international research and practical case studies, the keynote examines the complex ecosystem surrounding urban digital twins, bringing together planners, policymakers, researchers, technologists, and communities. It highlights how digital twins increasingly function as meeting points between multiple forms of knowledge — technical, political, social, and experiential — and why interdisciplinary collaboration is essential for their success. The talk critically reflects on the tensions between technological ambition and civic inclusion, exploring themes such as transparency, interoperability, participation, and trust. It also discusses how digital twins can become powerful environments for scenario exploration, urban experimentation, and collective learning, enabling cities to better navigate uncertainty and complexity in an age of rapid urban transformation. Ultimately, this keynote presents a vision of digital twins not as neutral technological systems, but as living socio-technical infrastructures capable of reshaping urban governance itself. The challenge ahead is therefore not only how accurately cities can be modelled, but how inclusively they can be imagined, negotiated, and governed through these emerging digital environments.

Prescriptive AI in Practice: Bridging Optimisation, Generative AI and Agentic Decision-Making

Bernardo Almada-Lobo

Universidade do Porto, Faculdade de Engenharia, INESC TEC, Portugal

Abstract. Prescriptive AI, viewed through the lens of mathematical optimisation and operations research, addresses complex business decision-making problems involving limited resources, multiple decision options and competing objectives. This talk considers the full decision pipeline: problem framing, model formulation, computational solution, implementation, monitoring and organisational adoption. The practical success of prescriptive AI depends less on algorithmic sophistication alone than on the quality of the translation between real-world decision contexts and formal optimisation models. In practice, this translation remains a major bottleneck. Objectives are often ambiguous, constraints are incomplete or tacit, data may be fragmented, and the operational consequences of a recommendation may be poorly understood. As a result, optimisation projects can fail even when the underlying mathematical model is technically sound. The talk will address the persistent gap between optimisation theory and deployment practice. While optimisation has generated substantial value in domains such as supply chain planning, logistics, production, revenue management, workforce planning and inventory control, many initiatives still face a significant risk of under-delivery. Common failure modes include incorrect problem framing, weak data readiness, brittle assumptions, infeasible or non-actionable recommendations, limited explainability, insufficient ownership by business users and inadequate post-deployment monitoring. Closing this gap requires moving from one-off model building to an operational lifecycle in which models are stress-tested, embedded in workflows, monitored for drift and revised as the business environment changes. Recent developments in generative and agentic AI create new opportunities to reduce these barriers. Generative AI can support the elicitation of decision-maker preferences, the structuring of unstructured operational knowledge, the drafting of candidate formulations and the explanation of model outputs in business language. Agentic AI can extend this role by orchestrating multi-step workflows that involve model formulation, solver-code generation, execution, debugging, infeasibility diagnosis, sensitivity analysis and human review. However, these capabilities should not be interpreted as replacing optimisation expertise. Rather, they create a new interface between human judgement, analytical modelling and computational decision support. This talk will discuss a cross-fertilisation agenda between optimisation, generative AI and agentic AI, with a focus on how these technologies should be calibrated to the decision at hand.

Net-Zero Communities through Life Cycle Thinking: Canadian Lessons and Global Implications

Kasun Hewage

School of Engineering (Okanagan Campus), Clean Energy Research Centre (CERC), University of British Columbia (UBC), Canada

Abstract. This keynote presentation discusses how life cycle thinking supports the transformation of communities toward sustainable, resilient, and net-zero futures. Drawing on Canadian research, practice, and policy experience, the presentation highlights how integrated life cycle approaches can move beyond conventional carbon accounting to inform practical decision-making across buildings, infrastructure, energy systems, waste management, water systems, and industrial processes [1–8]. The keynote features research conducted at the Life Cycle Management Laboratory (LCML) at the University of British Columbia, Canada, an internationally recognized research hub led by Kasun Hewage. LCML brings together engineers, scientists, policy researchers, postdoctoral fellows, visiting scholars, and graduate researchers to translate data-intensive sustainability research into actionable climate solutions. The laboratory's work is organized around six interconnected research themes: energy systems, urban development, water systems, waste management, construction and asset management, and industrial processes and products. Together, these themes provide an integrated platform for advancing life cycle–based pathways to net-zero communities. Supported by strong partnerships with government, industry, and community stakeholders, LCML has contributed to a substantial body of applied sustainability research, including more than 400 journal articles, 100 conference papers, and numerous technical reports that have informed real-world planning and implementation. This keynote presentation highlights selected success stories that demonstrate how life cycle thinking can be translated into practical strategies for reducing environmental impacts while strengthening community resilience. These insights are especially relevant to the interdisciplinary focus of ICCSA 2026.

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Machine Learning Based Methodologies for Grape and Wine Production

Pedro Melo-Pinto

University of Trás-os-Montes and Alto Douro, Engineering Department, Centre for the Research and Technology of Agro-Environmental and Biological Sciences, Portugal

Abstract. Wine production is a major area in the Portuguese economy. The sector accounts for approximately 2.6% of Portugal's GDP, and is crucial to the development of inland regions. Wine quality depends on grape quality, which is a result of different factors such as harvesting at the optimal point of maturity, or selecting the grapes according to quality features. The growing importance of precision agriculture demands novel methods to make the most out of the data generated. Machine learning approaches are particularly suitable for modelling complex processes, where too many arguments are involved. Many of the agricultural processes such as yield estimation or ripening fall into this category. However, several challenges may arise: even if models are available for particular cases, general models are difficult to come by, largely due to the high variability involved; with such models, there is a need for huge amounts of data, in a way which will not always be easy to obtain. This is particularly true in the case of grape production and the wine industry, where the number of grape varieties, climate, soil, etc., introduce a degree of variability that is uncommon in other sectors. One way of obtaining more information in such cases has been the use of images, whether RGB, multi-spectral, or hyperspectral. The use of images introduces additional challenges, such as data size and lighting conditions, which underscores the need for data-driven modelling methodologies. The use of machine learning (ML) techniques combined with images has been establishing itself as a viable alternative for predicting yields or quality parameters in grapes, and assisting with critical harvesting decisions. Several ML approaches have been proposed to handle such data characteristics, but selecting a suitable methodology that best addresses the problem under study and making sure it generalizes well is, most of the time, a cumbersome task. We will address three wine and grape production problems, yield estimation, grape quality assessment, and illness detection, presenting different difficulties. Yield estimation is a major aspect in the wine production industry. The number of berries is one of the most relevant yield aspects, and can be estimated using computer vision, namely image segmentation algorithms. Lighting is one of the key factors in computer vision approaches, and occlusions—which are common in this problem—can be minimized, but require estimation models to achieve reliable results. Early illness detection is, of course, of the utmost importance, with an impact on production and quality. Detecting early symptoms and distinguishing them from other conditions is a difficult task, which makes the use of machine learning algorithms advisable, using automatic visual inspection of the leaves, addressed as a pixel-based classification problem. However, the available datasets are limited and

complex to compile, as different diseases typically require very specific time-frames and locations. The use of generative models to overcome this obstacle, in conjunction with robust classification models, leads to models that are intended to be as general as possible. The evaluation of the grape's maturation profile based on the evolution of their oenological parameters over time is one of the most important aspects for ensuring wine quality, playing a decisive role in the definition of the optimal time for harvesting. The use of hyperspectral imaging combined with learning algorithms represents a faster and non-destructive grape ripeness assessment method. We focus in two fundamental aspects to address the resulting data variability: a possible wavelength bands selection (with the purpose of reducing the dimensionality of data without losing predictive power) and the generalization ability of the ML model under such demanding conditions.

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Addressing Mobility-as-a-Service Inclusive Design through the Engagement of Vulnerable Users: Future Perspectives for Italian MaaS

Sara Faedda[1(✉)], Valentina Costa[2], Tanja Congiu[1], Ilaria Delponte[3], and Chiara Garau[4]

[1] Department of Architecture Design and Urban Planning, University of Sassari, Via Garibaldi 35, 07041 Alghero, Italy
sarafaedda2@gmail.com

[2] Italian Excellence Centre for Logistics, Transport and Infrastructures (CIELI), University of Genoa, Genoa, Italy

[3] Department of Civil, Chemical and Environmental Engineering (DICCA), University of Genoa, Genoa, Italy

[4] Department of Civil, Environmental Engineering and Architecture, University of Cagliari, Via Marengo, 2, 09123 Cagliari, Italy

Abstract. Mobility-as-a-Service (MaaS) has been targeted for long for its transformative potential for enhancing accessibility and social inclusion by addressing physical, economic, spatial, and digital barriers faced by vulnerable users, including the elderly, disabled individuals, and those in marginal areas. This paper examines Italy's MaaS4Italy initiative, funded under the Italian National Recovery and Resilience Plan, thus revealing that initial pilots prioritized early adopters (e.g., commuters, younger users) while lacking systematic engagement with vulnerable social groups (VSGs). Drawing on literature review and empirical analysis -including Sardinia-based surveys with NGOs- the authors identify key digital accessibility requirements (WCAG compliance, universal design principles) and engagement barriers (digital divide, mistrust, consultation fatigue). A three-phase governance and deployment framework is therefore proposed: (i) public authorities setting accessibility standards; (ii) co-design via partnerships with NGOs; and (iii) centralized audits with iterative VSG involvement for monitoring. Findings underscore the need for hybrid public-private governance, integrating Artificial Intelligence for bias-mitigated user profiling and tailored services. Policy recommendations advocate tailor-made strategies to ensure equitable MaaS deployment, fostering inclusive national pilots and long-term sustainability.

Keywords: Mobility-as-a-Service · VSGs · NGOs · accessibility standards

1 Introduction

Mobility-as-a-Service (MaaS) has been targeted from the very beginning as a powerful driver for accessibility improvement and social inclusion, shifting the transportation focus from private car ownership to flexible, user-centric, and integrated multimodal

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mobility solutions [1]. By aggregating different transport providers into a single digital platform for planning, booking, and payment, MaaS addresses multiple dimensions of transportation disadvantage [2], stemming from objective factors (such as territorial divide) up to individual conditions.

In details, it may mitigate physical, economic, spatial, and temporal barriers leading to transport poverty, by offering affordable, integrated alternatives to private vehicles [3]. In this context, transport poverty can be conceptualized as a lack of accessibility that prevents individuals from meeting their basic needs and participating in society [4]. It does not only concern the lack of means of transport, but the lack of adequate access to essential activities. In other words, it adopts accessibility as a central operational concept for translating social justice into design practice. In the long term, MaaS gives policymakers the opportunity to shift from broad supply-side subsidies to user-based, person-centered incentive models, directly improving the equity and efficiency of transport subsidies for disadvantaged groups [5]. Territorial inequalities may be addressed, as well.In rural, remote, or island communities, where sprawling geography and low population densities make traditional fixed-route transit financially unviable [6], MaaS systems integrate flexible, crowd-sourced, and Demand-Responsive Transport (DRT) with high-capacity transit, effectively solving "first and last mile" gaps [7].

Within an intersectional perspective, similar context-related disadvantages may also overlap with personal conditions. In this direction, MaaS allows also vulnerable population empowerment through two main lines of action: i. reduction of physical and cognitive effort and ii. improvement of universal accessibility by design [8].

Door-to-door services may indeed be included within MaaS offer, restoring independence for those unable to operate a private vehicle [9]. At the same time, the combination of route planning, booking, and real-time updates into a single interface, should also drastically reduce the logistical effort and anxiety associated with trip chaining, which benefits elderly users and those with intellectual vulnerabilities [10].

Similar goals may indeed be pursued only mainstreaming universal design principles [11] from the initial steps of the process, thus considering the psychological, physical, and cognitive needs of individuals, creating a system usable by everyone without the need for specialized adaptation [12].

In this direction, as highlighted by [13], MaaS potential in terms of social inclusion and universal accessibility may be measured through a multi-dimensional approach focusing on transport service and infrastructures accessibility, as well as on digital platform design. The present contribution aims at applying a similar framework to MaaS4Italy initiative, funded by National Resilience and Recovery Plan (NRRP) and launched in 2021 [14]. Currently in the pilot phase, similar project aimed at defining a national platform for Italian MaaS, supporting data standardization and best-practices sharing among cities and territories involved in the experimentation [15].

Targeting effective pilot deployment, particular attention has been paid to the engagement of early adopters (e.g. younger users, commuters, etc.) [16]. Nevertheless, similar approach may translate into poor accessibility of the comprehensive system, both on the physical and digital sides, thus hampering the inclusion potential of a nationwide MaaS proposal for Italy.

In this direction, the present research addresses the identification of accessibility requirements for inclusive MaaS platforms, focusing on the engagement and needs of vulnerable users (Sect. 2). Subsequently, potential barriers to the design and deployment of accessible MaaS will be addressed in Sect. 3, thus identifying potential recommendations that guide policymakers through inclusive and accessible MaaS pilots. Conclusive remarks will be provided in Sect. 5.

2 Background

MaaS inclusive potential mainly relies on the mainstreaming of universal design principles from the very first steps, as well as on the engagement of vulnerable users within a participated co-design process [17].

2.1 Digital Accessibility

The main factors affecting the digital accessibility of mobility apps can be divided into two broad categories: technical and interface design factors (indicating how the app is built) and user-centric factors (depending on the resources and capabilities of the people using the app) [18].

Technical and interface design factors generally align with Web Content Accessibility Guidelines (WCAG) and usability heuristics tailored for mobile interfaces. To be more precise the main factors to consider are as follows:

- Perceivability and Visual Design: an accessible app requires sufficient text size, the ability for users to customize font sizes, and high colour contrast between text and backgrounds [19]. Common accessibility violations in mobile apps include low text colour contrast and the lack of alternative text (alt-text) for images, which prevents screen readers from describing visual content to visually impaired users [20]. Content should also not be placed too tightly on the screen.
- Operability and Navigation: The app must be easy to navigate and control. This includes providing adequate spacing between elements, sufficiently large buttons or icons (touch targets), and consistently placed navigational markers like “back” and “next” buttons [21]. Additionally, elements must have proper technical “focus” enabled; otherwise, they cannot be navigated using external keyboards or recognized by assistive technologies [22].
- Understandability and Clarity: Apps should use plain, everyday language, avoiding technical jargon and complex expressions [23]. Accessibility is also enhanced by intuitive features like autocorrect, clear error messages with constructive recovery solutions, and step-by-step guidance or pop-ups that assist users in completing tasks without confusion [24].
- Robustness and Assistive Technology Compatibility: The app must be technically built to work smoothly with integrated assistive technologies, such as Android’s TalkBack or iOS’s VoiceOver [25]. To achieve this, all interactive elements, input fields, and visual graphics must be correctly labelled in the application’s underlying code [26].

User-centric factors' accessibility is also heavily influenced by the digital inequality gap, which dictates whether a user can actually access and successfully operate the technology according to individual features and resources. Digital literacy and skills are identified as one of the strongest predictors of access to mobility services [27]. Users need "medium-related skills" (knowing how to operate a smartphone or browser) as well as "content-related skills" (knowing how to search for routes, assess the reliability of real-time info, and manage privacy settings) [28]. Material access to the physical technology is a prerequisite. This includes owning a capable smartphone, having a reliable data plan, and managing battery life and operating system updates [28].

From an individual perspective, a lack of trust can severely hinder accessibility. Fear of cybercrime, data leaks, phishing, and general privacy concerns often dissuade users from engaging with digital mobility platforms, especially when online payments or credit cards are required [29]. Digital flexibility is required to adapt to constant changes in the digital landscape. Frequent app updates, shifting to entirely cashless ticketing systems, or navigating sudden platform changes can create significant barriers for users with low digital flexibility [30]. Finally, as far as users' segments are concerned, vulnerability to digital exclusion in mobility frequently correlates with age (e.g., older adults facing cognitive or motor decline), lower income and education levels, physical or cognitive disabilities, language barriers, and lack of social support networks to help them learn the technology [31].

Being individual barriers not valuable aprioristically, a subsequent step would require users' engagement and involvement to address them properly.

2.2 Vulnerable Users' Engagement

In the context of transport digitalization, there is a risk that these systems, rather than helping, may increase the disadvantages of the most vulnerable groups [32]. In this sense, it is vital to involve all potential user groups in the design, testing and evaluation of innovative mobility solutions if inclusivity and accessibility are to be ensured [33].

In order to properly engage VSGs [34] in the planning process, their recruitment requires the adoption of diversified and inclusive strategies. One effective approach consists of creating partnerships with local associations that can operate as facilitators and can act as intermediaries between researchers, policy makers, and target groups [35]. These associations often have a direct relationship with local communities and vulnerable users, allowing them to facilitate communication, build trust and mediate [36].

A series of strategies have been identified from the literature based on direct experience [37]. n particular, studies emphasize the importance of integrating online and offline recruitment channels, especially when involving the elderly since digital-only approaches, such as emails, may exclude people with limited digital skills. Collaboration with organizations and associations, the use of attractive images, visuals and storytelling techniques as well as the employment of snowball sampling methods have been identified as effective instruments for participant recruitment [38]. he provision of incentives, including vouchers, discounts or minor gifts, has been demonstrated to facilitate the recruitment process and enhance the level of interest in participation. Furthermore, the organization of face-to-face events and the dissemination of the research outcomes may

enhance the likelihood and willingness to contribute to subsequent activities and engage in long-term initiatives.

Another effective strategy in reaching vulnerable population groups is through Communities of Practice. This concept has found numerous practical applications in a variety of fields including business, organizational design, public administration, education, professional associations, development projects and civil life [39]. As [40] highlight, the CoP constitutes a functional space in which diverse actors convene with a view to resolving actual problems. This approach constitutes an alternative operational method that can be employed to incorporate vulnerable groups within the planning process.

Finally, to address this challenge effectively, it is essential to adopt a 'tailor-made' approach calibrated to the specific characteristics of the reference population with a thorough understanding of its needs and a particular attention to the social groups at risk of exclusion.

2.3 MaaS4Italy User Profile

MaaS4Italy is a nationwide funded program that was launched in 2021, stemming from Italian NRRP resources (on their turn descending from Next Generation EU financing). It aims both at the design and deployment of a national database and repository supporting shared data standards on a national level, the so-called Data and Service Repository for MaaS (DSRM) [41]; as well as at implementing several pilots across the country. In detail, two subsequent selection rounds were implemented, the former one addressing capital cities and the latter in 2022 addressing regions on a wider scale.

As far as users' profile selection is concerned, MaaS4Italy envisages the engagement mainly of volunteer citizens recruited through information campaigns, mobility habit surveys, and experimental panels, with a minimum target of 1,000 users per pilot project.

During first phase (completed by the end of 2023), the pilot cities engaged users on a voluntary basis and at their own expense, forming panels through ex-ante, ongoing, and ex-post surveys to assess impacts on attitudes and mobility habits. Participation was low but qualitatively positive, as users reported satisfaction, increased travels, and reduced private car use [14]. Average users were recruited from metropolitan or partial populations, profiled by age (>16 years), gender, residence, employment, and transport modes used. Nevertheless, on an individual basis, selected cities and regions identified peculiar target groups to be addressed preferentially.

In details, three pilot cities and one pilot region explicitly refer to vulnerable target segments.

The city of Bari [42] for instance addresses among selected users' groups students, commuters, tourists and disadvantaged residents. Specifically, the latter group includes people with disabilities, pregnant women and families with children under the age of four, refugees and asylum seekers, unemployed people.

Turin, as well, targets two main clusters of users [43]: citizens and corporate users. Among the former group, particular attention has been paid to people with disabilities that benefit from dedicated incentives and support.

Rome, in its turn, addresses commuters, tourists, students and people with mobility impairments [44].

Emilia-Romagna region [45], finally, targets three main categories of resident commuting to larger cities, with particular attention paid to people with disabilities, people living within inner areas using Demand-Responsive-Transport for their daily mobility and tourists.

First phase of MaaS4Italy does not show comprehensive and systemic commitment to vulnerable users' engagement. Despite fragmented references to people with disabilities and other fragile categories, an integrated approach towards vulnerable targets is lacking, thus leaving behind relevant users' groups, such as the elderly. In this direction, early adopters –commuters and tourists, above all, appear to be preferable testers of project first round [16].

3 Methodological Approach

Stemming from similar premises, proposed approach targets MaaS accessibility and inclusion potential through three main critical dimensions: i. the assessment of mobile apps features in terms of universal accessibility; ii. ways to engage vulnerable users' associations and NGOs within the co-design process; iii. role of public authorities and actors to foster the implementation of inclusive MaaS. These three steps indeed cover the entire process from the design of interface and functionalities to the deployment of mobility services.

3.1 Accessibility Checking Tool in European Legal Framework

Although WCAG are widely recognized, public authorities and regulators in both the European Union and beyond (e.g. in the USA) do not provide a single, fully automated official tool for assessing the accessibility of mobile mobility apps; instead, they define legal frameworks, standards and monitoring methodologies that combine automated checks with structured human evaluation [46].

In the EU, mobile apps -especially those of public sector bodies, among which MaaS apps may be listed- are covered by the Web Accessibility Directive and are expected to comply with the harmonised standard EN 301 549, which in turn references WCAG 2.1 AA (and is being updated in line with WCAG 2.2), while national monitoring methodologies prescribed by the Directive require in-depth audits and simplified checks carried out by trained evaluators, optionally assisted by automated tools (European Commission, 2016; European Commission, 2018).

In this direction, the European Accessibility Act (Directive (EU) 2019/882), by incorporating international technical standards of the WCAG 2.2 and EN 301 549, transforms accessibility from an accessory requirement to a primary functional requirement. In this sense, it shifts the focus from "assistance services" to an interface that can be used by anyone: if a website or platform such as MaaS is designed for a visually impaired person, it will be easier to use for everyone, including tourists or elderly people in low light or poor readability conditions. However, while the EAA provides the minimum legal framework for introducing minimum standards it must necessarily be accompanied by local policies that guarantee access and address the economic and cognitive barriers faced by the most vulnerable people [47]. The EAA goes beyond the fragmented view

of accessibility by imposing uniform, European-level requirements that are not limited to removing technological barriers but promote the structural adoption of the principles of inclusive design, design for all and universal design. These guidelines are particularly relevant for MaaS platforms, as the directive stipulates that the perception, operability and comprehensibility of digital services must be guaranteed for all users, regardless of their sensory or cognitive abilities. Italy transposes the European Accessibility Act (EAA) with the Legislative Decree n.82 of 2022, which implements the Directive (EU) 2019/882 on the accessibility requirements of products and services.

The adoption of these regulatory standards guarantees an inclusive user-centered digital infrastructure and ensures the same level of accessibility across different channels, reducing barriers for those with cognitive or sensory limitations. Although digital accessibility is an increasingly important issue in the European regulatory landscape, it cannot be separated from accessibility in real contexts. The website is only part of the experience, and having platforms that are truly inclusive and accessible continues into the physical environment.

In this direction, therefore, official practice converges on hybrid, standard-based evaluation -anchored in WCAG and EN 301 549- where automation is used mainly for large-scale or low-level checks (e.g. missing labels, colour contrast), and human judgement remains essential to assess more complex aspects such as operability, understandability, meaningful focus order, gesture complexity and real compatibility with assistive technologies in domain-specific apps like those for urban mobility [22]. Empirical analyses confirm that automated tools identify only partially issues in real mobile apps, underscoring the irreplaceable role of manual and user-involving evaluations [48].

Similar aspects hinder evidently the possibility to implement large-scale monitoring within MaaS4Italy initiative due to the high number of apps that aver been included into the different implemented pilots nation-wide. Despite some of the MaaS providers are present in more than one pilot, general structure of the initiative has the aim to implement an open ecosystem that could include incrementally more and more providers and respective apps.

In this sense, going beyond basic technical accessibility checks, could be extremely critical to assure equal access conditions to every app, within every pilot. Moreover, the absence of automated standardized process, may lead to a fragmented framework where traditional accessibility inequalities are transferred to the digital dimension [49].

Being human intervention unavoidable to perform similar evaluations, a potential step to be taken could be to engage vulnerable communities also within the design process to grant statistical representation of the target groups within every pilot, thus bypassing manual technical accessibility checks and corresponding arbitrary risks. In this direction, similar approach could indeed integrate official centralized audit that could support universal accessibility compliance from a more institutional perspective.

Going further with accessibility checks, is should be highlighted how being MaaS a mobility app, user-interface does not represent the only element to be evaluated in this direction. The possibility to include within user profile potential mobility impairment selecting by default universally accessible alternatives should be considered, as well [13]. Effort reduction principle implies indeed the presence of default options supporting seamless selection of journey options by different groups of users.

3.2 NGOs and Associations Role and Criticalities

Engaging associations from the early stages of the planning process is fundamental for ensuring a more inclusive and representative participation of users. These associations can play a key role as intermediaries between researchers, plannersand end users, facilitating communication and helping to reach groups that are often difficult to involve through traditional engagement channels. However, in practice, their involvement does not always occur in a systematicand effective way. Nevertheless, it should be recognised that vulnerable social groups, are frequently designated as "hard-to-reach", signifying groups that are underrepresented and marginalised in public debate [36]:

- Structural barriers: resulting from the use of inadequate communication channels, the so-called "digital divide" and a widespread lack of specific skills within institutions.
- Psychological and social factors: such as scepticism towards authorities, systemic mistrust and the absence of representation that truly reflects the needs of these groups.
- Methodological limitations in engagement: late planning that excludes VSGs from decision-making stages as well as poor inclusivity due to inadequately trained staff, and a lack of incentives to encourage participation [50].

Exploring the nature of these barriers, as highlighted by [33], time constraints often represent a significant challenge, as consultation processes can be long and time-consuming, potentially leading to what is commonly referred to as "consultation fatigue" among participants.

In addition, local authorities and project coordinators may lack the necessary skills to effectively plan and manage participatory processes, while limited financial resources and insufficient personel capacties within public administrations can further constrain the organisation of meaningful engagement activities.

Dissatisfaction among participating organisations may also arise from shortcomings in the management of the participatory process itself.

As noted by [51], associations may feel excluded when they are not consulted with sufficient notice, do not have full visibility of the tasks involved, or are not actively included in the planning stages of the process. Such conditions may weaken trust and reduce the willingness of organisations to participate in future initiative [52].

Another critical issue concerns the risk of bias in the recruitment of participants, which can occur when it only relies on a single communication channel. For instance, the exclusive use of online channels for participant recruitment may primarily reach individuals with higher levels of digital literacy, thus excluding segments of the population with lower digital skills [37]. This limitation is particularly relevant when attempting to involve vulnerable social groups, such as older adults or individuals with limited access to digital technologies.

3.3 Role of the Public and Private Authorities Operator Agreements

Lack of control and monitoring to equal and universal access to MaaS platforms and services may also depend on the role and relevance that private and public actors playwithin the MaaS ecosystem.

MaaS4Italy initiative acts in this direction in a quite ambivalent way: data-sharing standards and platform are provided centrally, so that pilots share a common infrastructure, nevertheless, each of the involved territory is autonomous in defeding their governance mechanisms and models.

Public authorities should indeed define and identify data standards and accessibility mandates, complementing private firms' expertise in app development and real-time integrations [53, 54].

From an operational point-of-view, public-private partnerships in this direction prevail, since only few pilots have the aim to deploy a public-control app (Florence and Tuscany region are working in this direction), thus complicating the framework in which accessibility evaluation and vulnerable users engagement should be planned and implemented.

Similar approach positions users as active co-creators, particularly in rural settings, to enhance feedback-driven inclusivity [53]. This division bridges operational silos for broader service coverage [55].

It is therefore self-evident that similar hybrid approach leaves some relevant issues unsolved, not only in terms of governance and business effectiveness [56] but also in terms of social sustainability of the proposal.

In this direction, within a diverse society, public entities and policy-makers are required to act on multiple levels [57]:

- Set accessibility standards both in terms of physical and digital infrastructures, thus playing the fully public role of assuring equitable and universal access to new urban mobility services;
- Define public-private agreements with providers and actors involved within the ecosystem that include standards define at step 1. thus including universal accessibility criteria related to MaaS apps, mobility services and vehicles, equitable fares taking into account different mobility profiles. In this direction, similar elements would represent a pre-requisite and/or a rewarding element guiding providers selection;
- A third step of the enabling/monitoring role played by public promoter of the initiative should deal with the deployment of centralized audit and evaluations of universal accessibility conditions offered to users within the various pilots, thus engaging also vulnerable groups in the assessment process to feed an iterative approach.

Similar three steps' process aims at building a structured path for co-design and deployment of inclusive MaaS, to ensure proper involvement and empowerment of vulnerable categories that could benefit from MaaS paradigm, but that have been partially left behind from the initial pilots. An institutional and demanding workflow that aims at representing diverse mobility needs and behaviors, thus requiring at the same time a shared responsibility during the entire process.

4 Discussion

Identifying the workflow could therefore be crucial in supporting the progressive implementation and deployment of an inclusive MaaS approach during the pilot and subsequent phases.

In this direction, three different steps of recommendations have been identified:

- Empowerment and strategic framework: Public Authorities should play the role as primary coordinator who sets requirements and rules for societal equity and the compliance with accessibility standards. PA should also set the strategies for properly involving VSGs;
- Co-design process: a second step in which to translate the standards set in step 1 in operational requirements for a collaborative engagement. It translate standards in official agreement. In this step association play a key role as parties of interest by defining requirements with the PA;
- Institutionalisation and accountability: monitoring and long-term governance with association actively designated since the initial phases.

Adopting a structured, multi-step approach ensures that inclusivity is incorporated across all stages of MaaS development, from strategic planning to long-term governance. The ensuing sections of this paragraph will explore how these principles can be operationalised to create requirements for inclusive travel planning. These criteria are then enhanced through the use of AI-driven solutions for profiling users' needs and delivering tailored, on-demand services.

Similar tool may support in the long run the transition from the preliminary pilots based on early-adopters experiences to wider public applications, thus including vulnerable users. The analysis of massive data concerning mobility behaviours performed by AI tools could indeed support policy makers and MaaS providers to identify relevant factors and variables related to specific potential barriers for vulnerable groups (such as physical effort; presence of slopes; safer routes, etc.).

An AI-based transition roadmap from early testbeds to regular and inclusive MaaS proposal could indeed feed and speed-up participatory workflow, through the capitalization of the collection and processing of massive behavioural data and preferences.

At urban level AI-based solutions could also impact physically on users' experience of multi-modal journeys. The co-design process could indeed benefit from massive data collection and processing to improve both available transport services and platform universal accessibility, through a crowd-sourced approach.

4.1 Participatory Approach for Defining Criteria Oriented to Vulnerable Users' Needs

In the context of the design of inclusive transport systems, the establishment of a multi-step process has been identified as a fundamental prerequisite. A subsequent investigation into the mobility needs of vulnerable groups is recommended, with the objective of defining criteria for the development of tailored travel alternatives. In this context, co-creation processes represent a key strategic approach, enabling the active involvement of end-users throughout the design phases [37].

As [58] stated, these processes are typically operationalised through a combination of participatory methods, including interviews, focus groups, interactive workshops, and living labs, which allow for the collection of both qualitative and contextualised insights [37, 40, 51]. Such approaches facilitate a deeper understanding of users' experiences, constraints and preferences.

In this perspective, interviews and focus groups can be regarded as qualitative tools which are considered essential for the purpose of gathering first-hand experiences and gaining an in-depth understanding of individuals' capabilities, limitations and requirements [40, 59, 60]. The utilisation of these methods facilitates the identification of needs that are frequently eluded by quantitative surveys [61]. Specifically, focus groups are frequently considered as a functional approach for discussing and validating previously collected data through the interaction among participants, while also facilitating discussions within a selected small group [47].

The recommendations resulting from participatory methods and user engagement activities provide the empirical basis for defining a set of criteria designed to guide the design of inclusive MaaS travel options. In this regard, the potential of artificial intelligence to dynamically profile users' needs and enable adaptive, on-demand mobility services is significant.

The issues highlighted in the literature are also reflected in the empirical activities conducted as part of this research. As part of the PNRR-funded project to develop a MaaS platform for Sardinia, a survey was conducted to analyse the mobility habits of vulnerable people and their propensity to use digital tools for this purpose.

The questionnaire was developed and designed in collaboration with the Italian Multiple Sclerosis Association (AISM) whose contribution helped refine both the structure and the language of the survey in order to improve accessibility and comprehension for participants with different cognitive and physical. The survey was disseminated both at local and national level, using a multi-channel strategy integrating both online, via digital platforms and official social media channels and face-to-face administration methods to ensure wide dissemination and facilitate participation among users with varying levels of digital literacy.

AISM played a particularly important role in this phase, helping to reach people with disabilities and other vulnerable groups through its local branches and communication channels. The University of the Third Age (UTE) of the city of Alghero (Sardinia, Italy), played a significant role in facilitating communication with elderly people at a local level. For their involvement a face-to-face event as being organised in order to present the research project and distribute the questionnaire.

Despite the involvement of associations that acted as intermediaries between researchers and potential end users, as well as the use of both online and offline dissemination channels, the sample actually reached was limited. In the case of the questionnaire on mobility habits, 31 responses were collected, while the second questionnaire recorded 23 participants. The limited sample size can also be partially ascribed to the temporal constraint, as the involvement of vulnerable groups requires long-term engagement process capable of establishing trust between the different parties involved [37]. Therefore, the empirical phase was not intended to achieve statistical representation but rather to gather preliminary insights into mobility habits and attitudes towards assistive technologies among vulnerable users thorough the involvement of key informants.

Future research should involve a larger sample of vulnerable users to ensure statistical validity.

4.2 AI for Profiling Users' Needs and Managing on-Demand, Tailored Services

Artificial Intelligence (AI) may play a crucial role in profiling vulnerable users' behaviours and needs more precisely, thus enabling a more tailored, effortless and seamless travel experience. AI-driven profiling in MaaS extends indeed far beyond basic demographic data to capture the dynamic, context-dependent nature of individual mobility necessities.

From a methodological point-of-view, the mainstreaming of similar algorithms into the centralized repository of MaaS4Italy initiative – one of the distinctive features of the project- may support increased levels of accessibility and inclusiveness, thus relying on public action, only.

By leveraging Machine Learning (ML), for instance, AI synthesizes massive volumes of heterogeneous data -including historical travel patterns, real-time traffic, passive smartphone sensors, and socio-economic characteristics [62]. Through unsupervised learning and Natural Language Processing (NLP), AI can mine unstructured, crowdsourced data like app reviews to extract latent behavioral patterns and psychological traits [63].

By processing this detailed data, AI enables a more effortless and seamless experience specifically tailored for vulnerable groups in several critical ways. In this direction, AI deployment could effectively support the three-phase pathway towards a more inclusive MaaS proposal, especially referring to the two latter steps. Both within the co-design and institutionalization phases AI could contribute to detect and mitigate potential biases in service allocation and bundle proposal.

Knowledge-based AI frameworks use logic rules to combine a user's specific profile with contextual data (such as weather or traffic disruptions) to automatically filter out unsuitable transport modes and recommend personalized alternatives [64]. For elderly users or those with disabilities, AI can learn routine behaviors and autofill travel parameters or pre-select options, significantly reducing the cognitive burden and digital literacy required to navigate complex apps [65]. Furthermore, potential integration with wearable sensors deploying ML can monitor stress levels in frail older individuals, providing data that could be used to suggest more comfortable, less congested, and safer routes. During field operations -both during pilot as well as further upscaling steps- AI could also contribute positively in the perspective of MaaS providers to optimize service supply and bundle, deploying effectively anonymized mobility behavioral data and preferences, through dynamic and site-specific pricing mechanisms.

AI optimization reduces operational waste for MaaS providers, potentially lowering service prices to levels that attract users from economically disadvantaged regions [62]. AI-driven dynamic pricing models can analyze a user's price sensitivity and offer tailored mobility bundles, monthly allowances, or targeted subsidies, ensuring that shared transportation remains a financially viable alternative to private car ownership for low-income households [66].

For vulnerable users living in suburban communities or transit deserts with poor public transport access, AI models can identify unmet demand and optimize the placement of shared mobility options [67]. AI dynamically deploys services like ride-hailing or micro-mobility to provide essential first- and last-mile connectivity.

Notwithstanding, to guarantee that deep profiling benefits vulnerable groups without reinforcing existing inequalities, AI systems must be carefully designed to mitigate algorithmic bias [68]. If a dispatch algorithm is trained predominantly on data from affluent neighbourhoods, it may inadvertently learn to offer fewer services or longer wait times to marginalized areas, exacerbating social inequality. By embedding fairness constraints -such as equalized odds or demographic parity- into machine learning pipelines, MaaS platforms can ensure that resources and vehicles are fairly allocated, preventing the system from disproportionately denying services based on a user's demographic or socio-economic background [69].

5 Conclusion Remarks

In light of the experience gained from the MaaS4Italy and Sardinian MaaS projects in transport planning, the involvement of associations and organisations representing vulnerable users emerges as a key element in bridging the communication gap between policymakers and end users for the deployment of a universally inclusive Italian way to MaaS. In particular, the collaboration with AISM and UTE highlighted the importance of combining digital and non-digital engagement methods, involving trusted intermediaries and promoting long-term participatory process capable of fostering trust and participation over time.

These actors fulfil a pivotal intermediary function, aiding in the overcoming of mistrust, language barriers, and physical or cognitive limitations that frequently compromise the efficacy of conventional participation channels for the vulnerable social groups. At the same time, a critical issue has been identified. Despite the presence of regulatory frameworks addressing accessibility, particularly in relation to digital systems, the lack of effective enforcement mechanisms still limits the practical implementation. In this perspective, public authorities should assume a central coordinating role in the development of inclusive MaaS initiatives, as demonstrated by selected case studies. Their responsibility should extend beyond mere regulatory compliance, encompassing the active facilitation of stakeholders' engagement and integration of accessibility requirements from early design stages.

This is particularly relevant when addressing the needs of vulnerable users who require a tailor-made approach based on the target group involved in the process. In this regard, analysing vulnerable users' needs is essential for developing criteria for designing travel alternatives tailored to their actual needs [70].

Finally, the development of inclusive MaaS is best achieved by a structured and coordinated approach combining institutional leadership, stakeholders' facilitation and user-centered design to deliver tailored mobility solutions. It is therefore important to understand inclusive MaaS not merely as a technological innovation but as a governance challenge requiring coordinated, multi-actor and user-centered approaches.

Despite representing a preliminary study on potential inclusion and accessibility improvement for Italian MaaS proposal, the present research provides a comprehensive framework for future phases of MaaS4Italy. Limitations of the work are represented by the consideration of grey official literature from MaaS4Italy project, without the possibility to access pilot field data. Moreover, territorial focus has been represented by one case-study only.

Further steps would concern the analysis of pilot field data from the different territories, as well as the mapping of primary stakeholders to be addressed within the different territorial contexts, as well as the deepening of potential policy implications.

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