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Computational Science and Its Applications – ICCSA 2024 Workshops

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

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Preface

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

The conference was held in a hybrid form, with some participants present in person, hosted in Hanoi, Vietnam, by the Thuy Loi University. We enabled virtual participation for those who were unable to attend the event, due to logistical, political and economic problems, by adopting a technological infrastructure based on open source software (jitsi + riot), and a commercial Cloud infrastructure.

ICCSA 2024 was another successful event in the International Conference on Computational Science and Its Applications (ICCSA) conference series, previously held in Athens, Greece (2023), Malaga, Spain (2022), Cagliari, Italy (hybrid with few participants in presence in 2021 and completely online in 2020), whilst earlier editions took place in Saint Petersburg, Russia (2019), Melbourne, Australia (2018), Trieste, Italy (2017), Beijing. China (2016), Banff, Canada (2015), Guimaraes, Portugal (2014), Ho Chi Minh City, Vietnam (2013), Salvador, Brazil (2012), Santander, Spain (2011), Fukuoka, Japan (2010), Suwon, South Korea (2009), Perugia, Italy (2008), Kuala Lumpur, Malaysia (2007), Glasgow, UK (2006), Singapore (2005), Assisi, Italy (2004), Montreal, Canada (2003), and (as ICCS) Amsterdam, The Netherlands (2002) and San Francisco, USA (2001).

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

The ICCSA 2024 conference is structured in 6 general tracks covering the fields of computational science and its applications: Computational Methods, Algorithms and Scientific Applications – High Performance Computing and Networks – Geometric Modeling, Graphics and Visualization – Advanced and Emerging Applications – Information Systems and Technologies – Urban and Regional Planning. In addition, the conference consisted of 55 workshops, focusing on very topical issues of importance to science, technology and society: from new mathematical approaches for solving complex computational systems, to information and knowledge in the Internet of Things, new statistical and optimization methods, several Artificial Intelligence approaches, sustainability issues, smart cities and related technologies.

In the Workshops proceedings we accepted 281 full papers, 17 short papers and 2 PhD Showcase papers. In the Main Conference Proceedings we accepted 53 full papers, 6 short papers and 3 PhD Showcase papers from 207 submissions to the General Tracks of the conference (acceptance rate 30%). We would like to express our appreciation to the workshops chairs and co-chairs for their hard work and dedication.

The success of the ICCSA conference series in general, and of ICCSA 2024 in particular, vitally depends on the support of many people: authors, presenters, participants, keynote speakers, workshop chairs, session chairs, organizing committee members, student volunteers, Program Committee members, Advisory Committee members, International Liaison chairs, reviewers and others in various roles. We take this opportunity to wholehartedly thank them all.

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

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

July 2024

Osvaldo Gervasi
Beniamino Murgante
Chiara Garau

Welcome Message from Organizers

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

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

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

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

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

Nguyen Canh Thai

Organization

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

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Econometrics and Multidimensional Evaluation of Urban Environment (EMEUE 2024)

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

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

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

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

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

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Andreas Fricke	Hasso-Plattner-Institut für Digital Engineering, Germany
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Geomatics for Resource Monitoring and Management (GRMM 2024)

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

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Regenerating Brownfields Enhancing Urban Resilience Appeal (INFERENCE 2024)

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

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

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Martina Sinatra	University of Cagliari, Italy
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Development of Urban Mobility Management and Risk Assessment (MAINTAIN 2024)

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Multidimensional Evolutionary Evaluations for Transformative Approaches (MEETA 2024)

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

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

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Carmen Guida	University of Naples Federico II, Italy
Chiara Di Dato	University of L’Aquila, Italy

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

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Scientific Computing Infrastructure (SCI 2024)

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

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

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Paola Amoruso	LUM, Italy

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

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Marco Petrelli	Roma Tre University, Italy

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Massimiliano Bencardino	University of Salerno, Italy

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

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Smart Tourism (SmartTourism 2024)

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Brunella Brundu	University of Sassari, Italy
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Sustainable Evolution of Long-Distance Freight Passenger Transport (SOLIDEST 2024)

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Luigi Dall’Olio	University of Cantabria, Spain
Antonio Russo	University of Enna Kore, Italy

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

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Francesca Perrone	Sapienza University of Rome, Italy
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Specifics of Smart Cities Development in Europe (SPEED 2024)

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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.

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Ecosystem Services Accounting and AHP for Prioritizing Landscape Design Strategies in Urban Areas

Francesco Sica(✉), Fataneh Fatahi, Maria Rosaria Guarini, Cristina Imbroglini, and Francesco Tajani

Department of Architecture and Design, "Sapienza" University of Rome, 00196 Rome, Italy
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Abstract. The Ecosystem Services (ES) concept encourages research into a wide range of assessment techniques that may be used for planning and landscape design projects, particularly in urban settings. Starting with their categorization, a suitable evaluation technique might be linked to each of them to identify the highest inherent value that should be included in the decision-making processes.

After considering the operations of ES accounting and the various ES types (cultural, supporting, provisioning and regulating) that a single area is able to supply in the context of reference, an inter-sectorial assessment approach is required to prioritize the primary design line when evaluating the primary ES delivery in urban zone. The Analytic Hierarchy Process (AHP) is shown in this light as a useful tool for emphasizing the coherence of a mixed-set of ES supply and, concurrently, the relative relevance of each one compared to the ecological, socio-economic, and environmental aspects in urban region.

An integrated evaluation method based on ES accounting and AHP is put forth in order to assist with the individualization of urban planning and environmental design strategies case-specific. The paper concludes with an explanation of the findings from the Italian case study that the proposed method has evaluated.

Keywords: Analytic Hierarchy Process (AHP) · Ecosystem Services · Decision Making · Planning · Valuation

1 Introduction

Ecosystem services (ES) are gaining attention in different areas, including natural and social sciences [16]. They have the potential to enhance human well-being and economic prosperity [7, 11], regulate natural processes (e.g., water and air treatment, oxygen production, recreation areas), enhance the overall quality of urban society [3, 4, 6, 13, 21]. According to García and Estruch-Guitart (2022), these functions play a crucial role in the sustainability of Earth's different ecosystems.

The broad concepts of ES have been discussed for more than three decades [15], indicating long-held concerns that global changes will have a large and negative impact on terrestrial and aquatic populations. Much of the present emphasis on ecosystem services

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(ES) may be traced back to the Millennium Ecosystem Assessment (MEA), which was published a decade ago [23]. Beginning with the MEA Framework, several proposals for organizing the terminology and classification of ecosystem services have emerged, namely the Economics of Ecosystems and Biodiversity (TEEB 2010) and the Common International Classification of Ecosystem Services (CICES) [10, 13]. Additionally, Costanza et al. (1997) grouped ecosystem services into 17 major categories, focusing solely on renewable ecosystem services, while excluding non-renewable fuels, minerals and atmosphere [21]. Each form depends on geo-biophysical structures and processes, which vary in intensity, geographically, and temporally [2].

Anthropogenic impacts, particularly land-use and land-cover changes, as well as climatic variations, are among the major determinants influencing the qualities and quantities of ES supply. Land-use patterns and changes in land cover can be surveyed, spatially analyzed, and regionally assessed, providing direct insights into human activities and illustrating the relationships between ES supply and demand [2].

In recent years, the need for practical applications and tools related to the often conceptually employed ecosystem service (ES) ideas has become increasingly apparent [2]. Daily (1997) offers a comprehensive compendium detailing the description, measurement, and valuation of ecosystem services. Additionally, several assessment and valuation methods have been developed, by employing various biophysical and economic approaches [3–5, 13].

Recognizing and accurately quantifying ES are fundamental prerequisites for their valuation, irrespective of whether the valuation is conducted using biophysical, social, or economic strategies. Both in modern ES science and landscape design practices, the use and integration of these methodologies provide substantial hurdles [22].

Furthermore, it is imperative to acknowledge that valuing natural capital plays a central role in mainstreaming conservation efforts in modern societies [15]. Palomo et al. (2016) illustrate how the quantity and quality of delivered ES depend on different types of capital, resulting in various trade-offs that impact ES sustainability [11, 15].

Numerous methods and tools have been developed over the past decade for characterizing ecosystem functions and services in landscapes. Existing methods and data collection programs are poised to be integrated into the ES concept due to their thematic diversity (e.g., monitoring within the Long-Term Ecological Research (LTER) network) [2]. These methods encompass measurements, monitoring programs, mapping activities, expert interviews, statistical analyses, model applications, and transfer functions [6], as well as Analytical Hierarchy Process (AHP) [2, 5, 11]. Each is intended to solve a specific value concern, whether related to the environment or the socioeconomic structure of territory, especially in dense urban settings where the intricacy of linkages between various value-layers is heightened [11].

AHP is a technique developed to aid decision-makers in in systematically and structurally performing complex decisions [1]. This method combines both objective and subjective evaluations in an integrated structure, employing scales with a pairwise comparison matrix to help analysts organize the essential aspects of a problem hierarchically. Additionally, this method can measure the consistency of decision-makers' judgments regarding criteria and alternatives, facilitating the creation of pairwise comparisons between options to identify optimal solutions and alternatives [12].

The purpose of this contribution is to provide a decision-making framework based on the Analytic Hierarchy Process (AHP) for driving the individualization of landscape design strategies case-specifically [17, 18]. The way forward takes into account the measurement of ecosystem services, which vary by zone of the same urban context, and the mutual trade-off between the ecosystem services taking in analysis. The case study in Rome, Italy, involves the possibility of requalification of an area near the Sapienza University's Architecture Faculty located in Valle Giulia. This serves as a test case for the proposed assessment methodology based on AHP with ES accounting.

The overall work is organized as follows: Sect. 2 explains the materials and methods, including the methodological approach and the case study description (2.1); Sect. 3 provides results and comments above the procedure implementation; and Sect. 4 highlights the main conclusions of the work.

2 Material and Methods

2.1 Study Area

The *Valle Giulia* site, situated in proximity to historical, cultural, and educational hubs within the city of Rome, embodies a rich tapestry of environmental significance. It adjoins esteemed institutions such as the British Academy, National Gallery of Modern Art, Academy of Romania, Academy of Egypt, and shares borders with the stately *Villa Borghese*. This enclave encompasses open and verdant spaces intertwined with the architectural precincts of the *Sapienza* University, augmenting its allure with a botanical heritage, notably marked by the venerable oak trees dotting select locales. This arboreal presence serves as a poignant testament to the historical resonance embedded within the verdant realms of this territory (see Fig. 1).

In the quest for a spatial strategy that seamlessly integrates heritage preservation with contemporary needs, a thorough exploration of ecosystem services is imperative. Thus, an initial effort is made to outline and elaborate on the range of ecosystem services inherent to this area.

By employing the AHP method, this study systematically investigates the identification and assessment of ecosystem services within the study area. Through this detailed examination, it aims to provide insights that will guide prudent spatial planning efforts to optimize the utilization of these natural resources. This academic endeavor not only seeks to uncover the intricate ecological dynamics within the *Valle Giulia* site, but also aims to provide a blueprint for sustainable development, one that harmoniously blends the richness of its natural heritage with the demands of contemporary urban life.

2.2 Methodological Approach

The primary objective of conducting an ecosystem services assessment in this study has been to determine an appropriate methodology for planning activities within the designated study area. This involved categorizing the study area into three distinct zones, namely the semi-natural-urban zone, urban zone, and natural zone, based on their respective physical and biological attributes. Figure 1 depicts the indicated borders of these three distinct zones.

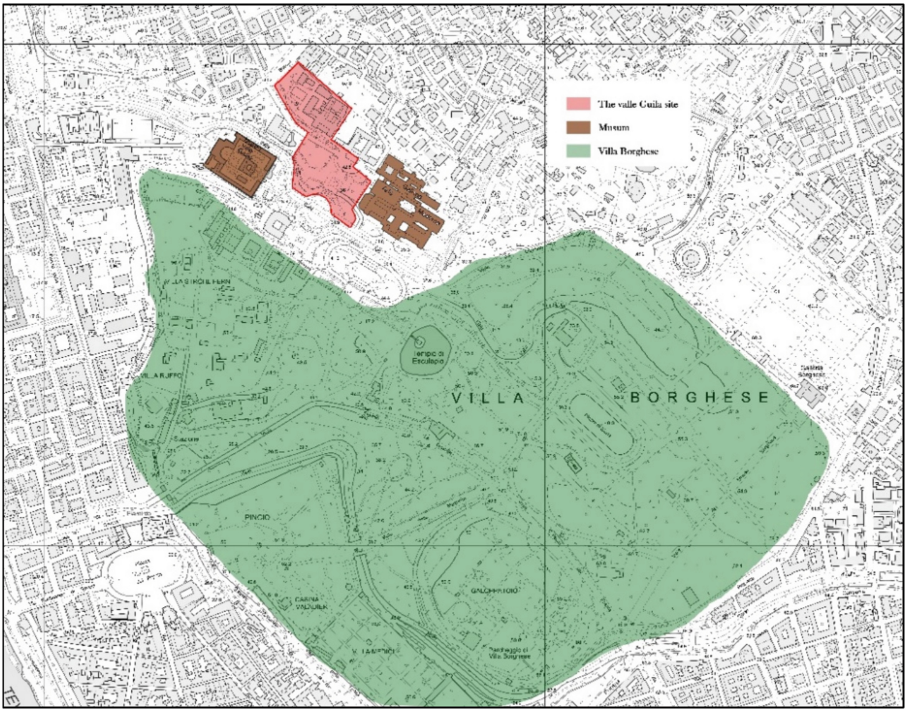

Fig. 1. The Valle Guilia site location and its surrounding users.

Following the zoning process, a comprehensive inventory of ecosystem services has been compiled. The main purpose of this inventory has been to identify the most significant ecosystem services associated with each zone. Subsequently, this information has been utilized to formulate a physical planning framework and land use strategies that take into account the ecosystem services, alongside other pertinent factors such as ecological and biological capacity. It is noteworthy that assessments of ecological and biological capacity have been carried out for each zone, although detailed discussion of these assessments is provided elsewhere in the article. This approach facilitates the development of sustainable planning and design strategies tailored to the unique environmental and ecological characteristics of each zone. By incorporating ecosystem services considerations into the planning process, the aim is to mitigate environmental degradation resulting from development activities.

In the subsequent phase of the study, the prioritization of the most significant ecosystem services for each zone has been developed by applying the AHP method. The outcomes of this assessment are intended to inform further stages of planning and design initiatives (Fig. 2).

2.3 Ecosystem Services in the Study Area

Ecosystem services are aspects of the ecosystems used directly or indirectly to induce human well-being, and some of them are easily observable, as they are involved in the

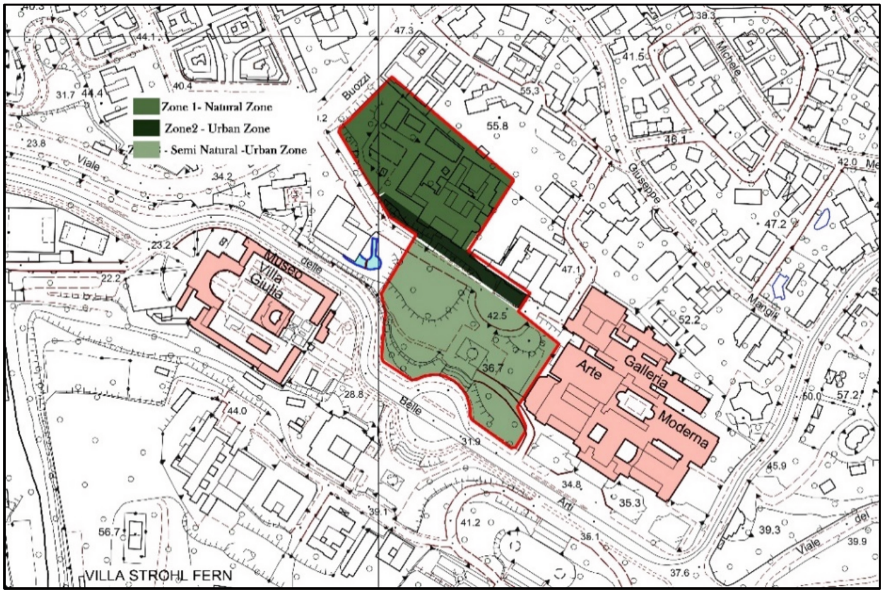

Fig. 2. The Valle Guilia site area and its Zones

economy (such as food supply or raw material). Nonetheless, society hardly perceives others despite contributing to these areas' social and economic value (including cultural services) [11]. This has caused inefficient use and progressive deterioration of natural resources [8]. According to the Millennium Ecosystem Assessment, the ecosystem services are classified in four main groups: supporting services (those that are necessary for the production of all other ecosystem services), provisioning services (products obtained by the ecosystems), regulation services (benefits obtained from the regulation of ecosystem processes) and cultural services (nonmaterial benefits people obtain from ecosystems) [3, 11]. Table 1 in the manuscript presents a comprehensive listing of the identified ecosystem services within the delineated study area.

2.4 Ecosystem Services Accounting and AHP

AHP is a well-known decision-making method that decomposes a complex problem into a multilevel hierarchical structure of objectives, criteria, and alternatives [19]. It is particularly effective in situations involving subjectivity and is well-suited for solving problems where decision criteria can be logically organized in schemes described by a directed graph [19]. AHP represents a structure with a unidirectional hierarchical relationship. AHP provides a decision tree structure with pairwise comparisons at each level of the tree. This method allows the calculation of the importance or weight of each group of ecosystem services as a percentage [11, 17, 18].

In the context of ecosystem services, AHP serves as a valuable tool for assessing and prioritizing various ecosystem services. By breaking down the decision-making process into manageable subproblems, AHP enables decision-makers to systematically

Table 1. Ecosystem services considered in the study

Cultural Services	Recreation and Tourism
	Education and Research
	Cultural Identity and heritage
	Mental welling
	Aesthetic Value
	Social relationship
Supporting services	Nutrient Recycling
	Biodiversity
	Heterogeneity
Provisioning Services	Biochemical and Medical
	Genetic Resources
Regulation Services	Climate Regulation
	Water Sanitary
	Nutrient Regulation
	Pollination
	Water Flow Regulation

evaluate and rank different services based on their significance. Moreover, its ability to handle subjective assessments and organize decision criteria into logical structures makes it particularly useful in this context. AHP's hierarchical structure and pairwise comparison approach facilitate a comprehensive analysis of ecosystem services, leading to informed and robust decisions [12].

In this stage, the data have been analyzed through the AHP method, which emphasizes weighting and prioritizing ecosystem services. The AHP method combines both objective and subjective evaluations in an integrated structure, based on scales with a pairwise comparison matrix. It assists analysts in organizing the essential aspects of a problem in a hierarchical format. Additionally, it measures the consistency of decision-makers' judgments regarding criteria and alternatives, enabling pairwise comparisons between options to choose optimal solutions and options [12].

The AHP framework for identifying and prioritizing the relative significance of ecosystem services consisted of three levels based on the construction of the evaluation hierarchy: 1) goal, 2) criteria and 3) alternatives.

2.5 Implementation Pathway

Expert Choice Software has been utilized in ecosystem services research as a valuable tool. This software is well-known for its robust decision-making capabilities, offering a structured framework to analyze and prioritize ecosystem services based on stakeholders' preferences and predefined criteria. Its application in this field has gained recognition due to its systematic assessment and prioritization of ecosystem services, considering ecological, economic, and social factors.

The methodology involved in using Expert Choice Software for ecosystem services research encompasses several essential steps:

Criteria Definition. Initially, researchers identify and define relevant criteria for evaluating ecosystem services, including ecological importance, economic value, social benefits, and feasibility of management actions.

Alternative Assessment. Different alternatives or management strategies aimed at enhancing ecosystem services are evaluated, ranging from conservation measures to sustainable land management practices.

Pairwise Comparison. Expert Choice facilitates pairwise comparisons between criteria and alternatives to determine their relative importance or effectiveness. Stakeholders assign weights to each criterion and alternative based on their judgment or empirical evidence.

Analytical Hierarchy Process (AHP). The AHP methodology embedded within Expert Choice Software is utilized to analyze the complex interactions and trade-offs among criteria and alternatives. AHP helps synthesize stakeholders' preferences and develop a comprehensive decision model.

Sensitivity Analysis. Sensitivity analysis is conducted to assess the robustness of decision outcomes to changes in criteria weights or input data. This process identifies key drivers of decision uncertainty and refines the decision model accordingly.

The Expert Choice Software was utilized to calculate the geometric means of every expert's pairwise comparison and form matrix A = (aij) for a consensus on n criteria, where the element aiI (i,j = 1,2, …, n) in matrix A denotes the quotient of weights of the criteria (Eq. 1). Then, the analysis started to normalize and find the relative weights for each matrix. The relative weights were given by the right eigenvector (W) corresponding to the largest eigenvalue max (λmax), as follows: [12]

$$\text{AW} = \lambda\text{max W } \mathbf{A} = \begin{vmatrix} a_{11} & a_{12} & a_{1n} \\ a_{21} & a_{22} & a_{2n} \\ a_{n1} & a_{n2} & a_{nn} \end{vmatrix} \quad (1)$$

When the local weights of the elements in each level were obtained, the overall weight of the quality attributes at the bottom level concerning the objective of the top level can be acquired by multiplying the local weights of related elements in each level.

In an entirely consistent pairwise comparison matrix (aij × ajk = aik), matrix A has rank 1 and λmax = n. In this case, the weights can be obtained by normalizing any of the rows or columns of A. When the comparison matrix is not fully consistent and the maximal eigenvalue is slightly greater than n, the consistency index (CI) is used for the coherence evaluation between the comparisons (Eq. 2).

$$\text{C} = \frac{\lambda\text{max} - \text{n}}{\text{n} - 1} \quad (2)$$

The consistency ratio (CR) is proposed to understand the consistency of the evaluation (Eq. 2), where RI is the average random consistency index.

$$CR = \frac{CI}{RI} \tag{3}$$

According to Saaty (1980), the CR < 0.1 is accepted, which can help decision-makers or evaluators confirm the consistency of the pairwise comparison matrix and the overall hierarchy [12].

3 Results and Discussion

The results have been initially examined within each group of ecosystem services, followed by an overall analysis and breakdown of ecosystem services within the study area.

Cultural Services. Within the realm of ecosystem services, the criteria weighting delineates the relative importance of each criterion when compared to others. In Zone 3, the prominence is evident, with Recreation and Tourism, Cultural Identity and Heritage, Mental Wellbeing, and Aesthetic Values garnering the highest weights, while Education and Research lag behind with the lowest weight. Shifting focus to Zone 2, the chart highlights Social Relationships as the dominant criterion, juxtaposed with Mental Wellbeing, which occupies the lower end of the spectrum. Conversely, in Zone 1, Educational and Research endeavors take precedence, contrasting starkly with the relatively diminished weight attributed to Recreation and Tourism.

Supporting Ecosystem Services. The criteria weighting of supporting ecosystem services reveals notable disparities across the study zones. In Zone 3, the highest weights are attributed to Biodiversity, whereas Nutrient Recycling obtains the lowest weight. Conversely, Zone 2 exhibits the highest weight for Heterogeneity and the lowest weight for Biodiversity. Interestingly, Zone 1 mirrors Zone 3 in terms of criteria importance, with Biodiversity holding the highest weight and Nutrient Recycling the lowest. Overall, the most critical criterion across all zones is Biodiversity, indicating its significance in supporting ecosystem functions. Additionally, Zone 3 stands out for its abundance of supporting services.

Provisioning Ecosystem Services. The assessment of provisioning ecosystem services showcases significant variations across the study zones. Within Zone 3, Genetic Resources emerge as the weightiest criterion, while Medicinal Resources lag behind with the lowest weight. Conversely, in Zone 2, Genetic Resources command the highest weight, compared with Medicinal Resources, which garner the lowest weight. Transitioning to Zone 1, Genetic Resources once again reign supreme in terms of criterion importance, boasting the highest weight, while Ornamental Resources trail with the lowest weight. Overall, Genetic Resources stand out as the paramount criterion across all zones.

Regulation Ecosystem Services. Significant variations emerge across the study zones. Zone 3 notably assigns the highest weighting to Pollination, while Nutrient Regulation receives the lowest weight. In contrast, Zone 2 allocates the highest weight to Pollination and the lowest to Nutrient regulation. Surprisingly, in Zone 1, water flow regulation takes precedence with the highest weight, while Nutrient regulation obtains the lowest. Overall, Pollination emerges as the most critical criterion across all zones, underscoring its pivotal role in regulating ecosystem services.

The outcomes derived from the evaluation of ecosystem services across various zones offer valuable insights that can profoundly impact planning and management strategies. By leveraging these findings, decision-makers can tailor resource allocation and development initiatives to maximize the benefits derived from different ecological zones.

For example, by going into depth the implications of prioritizing education-related ecosystem services in Zone 1, given its substantial weight in educational services, this zone presents a ripe opportunity to focus on environmental education programs. By implementing targeted initiatives such as school curricula centered on biodiversity conservation, soil conservation on slops, community workshops on sustainable practices, or nature-based learning experiences, stakeholders can foster a deeper understanding and appreciation for the local environment among residents and visitors alike.

Similarly, in Zone 3, where pollination services reign supreme, strategic interventions can be devised to bolster pollinator populations and enhance ecosystem resilience. This could involve initiatives such as establishing pollinator-friendly habitats, promoting organic farming practices that minimize pesticide use, or conducting public awareness campaigns to highlight the crucial role of pollinators in food production.

Moreover, for zones prioritizing medicinal services, there exists an opportunity to harness the therapeutic potential of native plant species. By creating medicinal plant gardens or supporting local herbalists in sustainable harvesting practices, communities can not only preserve traditional knowledge but also promote natural healthcare solutions that are culturally and ecologically aligned.

In essence, by integrating the valuation of ecosystem services into planning and decision-making processes, stakeholders can foster holistic approaches to land use management that prioritize environmental sustainability, community well-being, and economic prosperity. These efforts underscore the importance of recognizing and capitalizing on the multifaceted benefits that ecosystems provide, ultimately leading to more resilient and harmonious human-environment interactions.

4 Conclusions

Utilizing a structured decision-making approach in assessing ecosystem services proves indispensable for effective planning and informed choices. Ecosystem services, crucial for both human well-being and environmental sustainability, encompass a wide array of benefits, including clean water provision, pollination, and carbon sequestration. By employing a structured methodology such as the Analytic Hierarchy Process, several advantages emerge:

i. Decision-makers can systematically prioritize ecosystem services based on various factors such as ecological significance, economic value, and societal benefits. This systematic approach ensures optimal resource allocation and effective environmental asset management;
ii. AHP facilitates the evaluation of trade-offs between different ecosystem services, enabling decision-makers to navigate competing priorities and resource constraints effectively;
iii. AHP fosters stakeholder engagement in ecosystem services evaluation by providing a transparent and systematic process. This inclusive approach promotes collaboration and consensus-building among diverse stakeholders;
iv. Insights derived from AHP analysis inform policy and planning decisions related to ecosystem management, conservation, and sustainable development. Informed decisions, in turn, contribute to environmental resilience and human well-being.

In essence, structured decision-making methodologies like AHP play a pivotal role in valuing ecosystem services and integrating them into planning processes. By offering a rigorous and systematic approach, AHP empowers decision-makers to make choices that support sustainable development and environmental stewardship. The next stage of the research is to investigate the interlinkages between ecosystem services using a collaborative approach targeted at meeting ES supply and demand in connection to people's tangible needs.

Note. All the authors of the current study contributed equally to its creation, which was done as part of Sapienza University of Rome's continuing minor research project, "ECO-think: Integrating the ECOsystem services by nature in urban environment".

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