PUBLIC SPACES FOR COMMUNITY CAMPUSES AND UNIVERSITIES

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INU Edizioni Srl
Via Castro Dei Volsci 14
00179 Roma
Tel. 06 68134341 / 335-5487645
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www.inuedizioni.com
Iscrizione CCIAA 81 4890/95
Iscrizione al Tribunale di Roma 3563/95

Finito di stampare
Luglio 2025
Officine Grafiche Francesco Giannini & Figli SpA

In copertina
Copenhagen: detail of the Søndre Campus (photo by Marichela Sepe)

ISBN: 978-88-7603-269-1 (e-Book) €. 0,00
Open access http://www.inuedizioni.com

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CONTENTS

A simulation-based urban design methodology towards safety-conscious public spaces

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Antinisca Di Marco[**]

Introduction

In recent years, the growing incidence of both natural and anthropogenic disasters—exacerbated by climate change and the intensification of urban dynamics—has prompted renewed attention to the role of urban planning as a means of risk reduction and resilience building. In this context, pre-disaster planning emerges as a key practice for anticipating the consequences of critical events and developing multi-scalar strategies aimed at enhancing safety and preparedness in urban settings (FEMA, 2017; IPCC, 2023; Otsuyama & Maki, 2018). This paper proposes a methodology grounded in agent-based simulation to support the design of safer public spaces, specifically focusing on open areas within university campuses. The proposed approach integrates simulation and design to evaluate existing spatial layouts' performance under stress and explore alternative configurations that optimize evacuation dynamics and mini-

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mize risk (Eugeni et al., 2023; Di Ludovico et al., 2025). Traditional urban design processes often rely on pre-defined planning norms or heuristic criteria, with limited mechanisms for empirical verification. As a result, spatial decisions are frequently made in the absence of robust evidence on their real-world effectiveness, particularly in crisis scenarios. The methodology discussed here contributes to an emerging research niche that challenges this paradigm, promoting a data-informed approach that couples dynamic simulations with urban design (León & March, 2016; Fallah et al., 2014). Rather than supporting normative assumptions, simulation allows for the generation of synthetic yet plausible scenarios that reflect complex human behaviours under stress. These scenarios provide planners with operational metrics—such as evacuation times, congestion patterns, and spatial accessibility—that can inform more resilient spatial configurations. This logic has already been tested in previous case studies involving historical city centres and suburban university districts, confirming its adaptability and diagnostic potential (Eugeni et al., 2024a; Sacco et al., 2023). At the core of this methodology is a simulation environment developed using the GAMA platform (Taillandier et al., 2010, 2018), which supports agent-based modelling of crowd behaviour during emergencies. The platform allows for detailed representations of the built environment, crowd dynamics, and individual decision-making, making it particularly suitable for simulating evacuation scenarios triggered by earthquakes, fires, or other hazards (Iskandar et al., 2023; Wang et al., 2015). This simulation tool is integrated within a broader urban analysis framework inspired by the concept of the Digital Twin—a dynamic, data-driven model of urban space that not only reproduces the morphology of the built environment but also serves as a decision support system for testing spatial interventions (Sacco et al., 2023; Eugeni et al., 2024c). By incorporating GIS data, behavioural algorithms, and spatial performance indicators, the simulation environment enables stakeholders to visualize, evaluate, and compare design alternatives in terms of risk mitigation and emergency responsiveness (Benaben et al., 2021; Pluchino et al., 2014). The article is structured into five main sections. Following this introduction, section 2 presents the methodological framework in detail, outlining the architecture of the simulation model, the data sources, the calibration process, and the behavioural parameters. Section 3 introduces the three selected case studies: the Coppito (STEM departments), Roio (engineering departments), and city centre (human sciences department) campuses of the University of L'Aquila. These campuses were chosen for their strategic relevance and spatial heterogeneity within the post-earthquake urban context. Section 4 reports the results of simulation experiments, comparing the performance of current layouts with optimized design scenarios. The analysis focuses on evacuation time, crowd distribution, and critical bottlenecks, offering insights into how spatial interventions can enhance safety. Finally, Section 5 offers a critical reflection on the strengths and limitations of the approach, discussing future research directions, including integration with real-time data and expansion to multi-hazard scenarios.

Methodology

The methodological approach adopted in this study is grounded in the integration of agent-based simulation and safety-oriented urban design, with the primary goal of assessing and enhancing the emergency performance of public open spaces. The focus is particularly directed at university campuses, which often present complex morphologies and high population densities, making them highly sensitive to risks induced by natural or anthropogenic events. The method unfolds through two interdependent phases, which form an iterative loop rather than a linear progression. In the first phase, a simulation of the current spatial configuration is conducted. This phase involves the development of an agent-based model capable of reproducing crowd dynamics during an emergency evacuation, considering the actual layout of open spaces, the location of buildings and their relative exits, and the spatial distribution of safe zones. The simulation outcomes provide a diagnostic assessment of the site's criticalities, highlighting problematic areas in terms of crowd congestion, insufficient capacity of emergency gathering points, or delays in reaching safe areas by individuals. The behavioural logic implemented in the model draws upon established principles in evacuation science, with particular attention to the influence of spatial constraints on pedestrian movement, as explored in works such as Shiwakoti and Sarvi (2013) and Wang et al. (2022). Based on diagnostic results, the second phase involves the formulation of spatial interventions aimed at improving the system's evacuation performance. These interventions, designed within a GIS and simulation-integrated environment, may concern the repositioning or expansion of assembly areas, the modification of pedestrian circulation paths, or the removal of spatial barriers that hinder egress. Once implemented, the new scenario undergoes a second simulation, which allows for a comparative evaluation against the baseline condition. This cyclical process, based on successive iterations of simulation and redesign, enables the progressive refinement of spatial solutions and the validation of design choices through measurable indicators. As emphasized in Radianti et al. (2013) and Liu and Lyu (2019), such a feedback loop is essential for transitioning from static, rule-based planning approaches to adaptive, performance-oriented spatial design. The spatial model is constructed using a combination of open-access and institutional datasets. These include orthophotos and topographic maps for the reconstruction of the site's morphology, vector data on buildings and pathways, and population estimates derived from the University's institutional records and statistical sources. The modelling environment is developed within the open-source GAMA platform, which supports spatially explicit agent-based simulations with customizable behavioural parameters (Taillandier et al., 2010; 2018). Each agent within the model represents an individual actor with specific attributes, such as movement speed and decision-making patterns, and can react dynamically to environmental stimuli and the behaviour of surrounding agents. Simulation scenarios are evaluated using a set of performance indicators commonly adopted in evacuation studies. These include total evacuation time, average and peak crowd density in critical zones, and the proportion of agents reaching safety within a defined time threshold. Such indicators allow for the quantitative comparison of the baseline and optimized scenarios and provide empirical evidence to guide spatial planning decisions, as also demonstrated in the work of Bretschneider and Kimms (2012). To ensure the robustness of the model, validation procedures include internal consistency checks, sensitivity analysis, and consultations with domain experts.

Case studies

The methodology described in the previous section has been applied to three case studies, all located within the university system of the University of L'Aquila. These campuses differ significantly in terms of their geographic location within the urban and peri-urban fabric, as well as in their morphological and functional characteristics. The following section provides a concise overview of the three sites, with particular attention to the spatial configuration, maximum occupancy capacity of the buildings, and the location of the designated emergency assembly areas. All data were retrieved from the official institutional portal dedicated to safety and emergency planning[1].

[1] Web page with information about each campus of the University of L'Aquila https://www.univaq.it/section.php?id=2211

The first campus is situated in the hillside locality of Roio, specifically on the summit of Monte Luco, approximately 1000 meters above sea level and about 10 kilometres from the historic centre of L'Aquila. This site hosts engineering programs, administrative offices, and research laboratories. The campus comprises seven buildings, five of which are arranged in a circular formation around a central open space featuring green areas, tree-lined walkways, and parking facilities. Under full occupancy conditions, the campus can accommodate up to 3.186 individuals, including students, academic and administrative staff, third-party personnel, and individuals with disabilities. There are four designated emergency assembly areas located in proximity to the open spaces adjacent to the buildings with the highest occupancy loads.

The second campus is located near the Coppito district and lies adjacent to the "San Salvatore" hospital complex. It hosts the departments and degree programs of information science and mathematics, applied clinical sciences, biotechnology, physics, and chemistry. Approximately five kilometres from the city centre, the campus consists of four main buildings arranged in parallel and separated by shared open spaces and parking areas. The maximum occupancy is 4.245 individuals. Eight emergency assembly areas are available, predominantly located in areas currently used for parking.

The third campus is located in the historic centre of L'Aquila and hosts the Department of Human Sciences and its associated academic programs. It consists of a single building with a total capacity of 1.766 individuals. A single emergency assembly area is located in the square in front of the building.

To estimate the potential capacity of the emergency assembly areas, a value of 2.5 square meters per person was adopted. This standard reflects the need to ensure adequate comfort and safety during prolonged waiting times, which are likely to occur in the event of a natural disaster.

The main features of the three campuses are summarized in Table 1. As will be discussed in the following section, their diversity in terms of spatial configuration and urban context offered an ideal opportunity to test the methodology across a range of functionally similar but spatially distinct environments.

Table 1 - *University of L'Aquila campuses' summarized description and indicators (elaboration by authors)*

Campus	Edificio	Maximum capacity	Emergency assembly areas	Maximum capacity
Roio - Engineerings	A	1386	1	435
	B	584	2	4921
	C	1020	3	64
	E	95	4	98
	F	24		
	G	57		
	H	20		
Coppito - STEM disciplines	A	1093	1	441
	B	300	2	369
	C	1458	3	473
	D	1344	4	392
	E	50	5	560
			6	824
			7	493
			8	491
Historic centre - Human sciences	A	1766	1	1142

Results

The simulation framework relies on a set of general parameters which are consistent across all case studies. These include: the total number of individuals evacuating from each building and navigating toward designated emergency assembly areas via the shortest available path; the time taken to reach these areas; and the progressive occupancy rate of each emergency zone over time. The simulation outcomes are organized into two scenarios: the first (Scenario 0) corresponds to the current spatial configuration of each campus, while the second (Scenario 1) reflects an optimized layout developed through the application of safety-oriented urban design strategies. The simulation code was custom-developed by the authors and calibrated to ensure effective integration between the modeling environment and geospatial data preprocessed within a GIS framework. These spatial data constitute the foundation of the modeling process. At the end of each simulation run, a georeferenced raster output is generated, representing the level of crowding (or "crowdness") along the pedestrian paths used during evacuation. This output can be directly overlaid onto the original spatial data to enable comparative and visual analysis.

Figure 1 - *Scenario 0 (current spatial configuration) for the three university campuses (elaboration by authors)*


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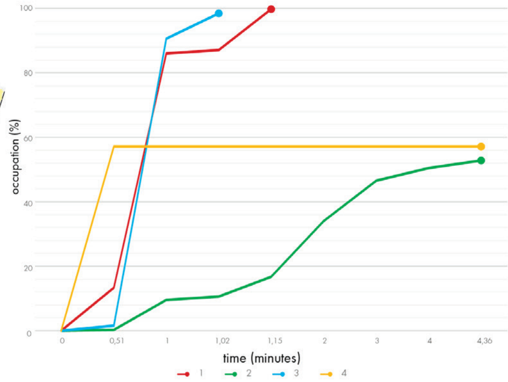
100
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occupation (%)
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0,51
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1,02
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3
4
4,36
time (minutes)
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6
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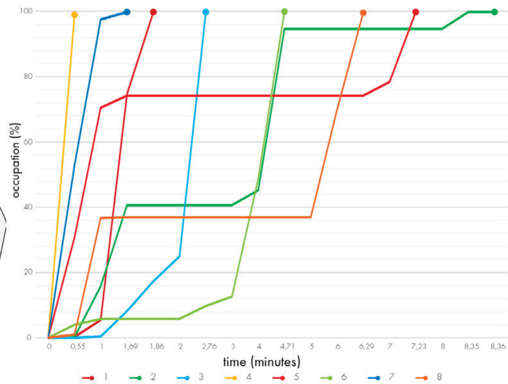
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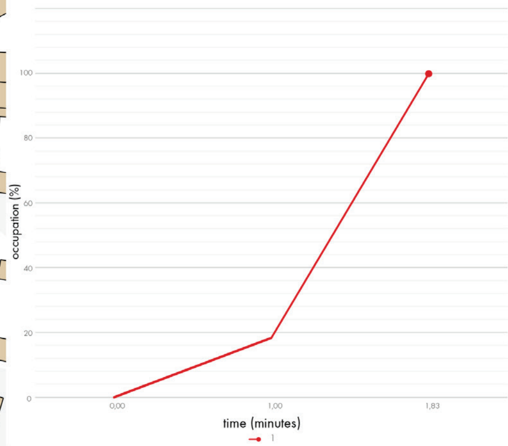
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40
20
0
occupation (%)
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1,00
1,83
time (minutes)
1

Scenario 0 – Existing conditions

The results obtained from Scenario 0 vary significantly across the three campuses, reflecting their differing morphological and functional contexts (Figure 1). In the case of the Roio campus, all agents successfully reach the designated emergency areas within 4.3 minutes of the simulation's start. Two of the four available safe zones reach full capacity, while the remaining two stabilize at approximately 60% occupancy. By contrast, the outcome for the Coppito campus reveals more critical issues: all eight emergency areas fill to 100% capacity, the last one doing so after 8.4 minutes, yet approximately 200 agents (out of a simulated total of 4,245.

of 4,245) remain unaccommodated. This indicates that, under current conditions, the available emergency space is insufficient to meet the demand. A similar situation emerges at the Humanities campus. The single available assembly area reaches its full capacity in just 1.83 minutes, leaving nearly 800 agents without a designated safe zone. In summary, the simulation results for Scenario 0 suggest that only the Roio campus currently possesses the spatial infrastructure necessary to accommodate a complete evacuation, based on the parameters and boundary conditions defined for the study. It is important to note that, especially in the case of the Humanities campus, several agents are forced to traverse segments of public roadway, external to the campus and not specifically designated for pedestrian use, to reach the emergency area.

Scenario 1 – Optimized spatial configuration

Following the assessment of existing conditions, a second round of simulations was conducted incorporating a series of safety-based urban design (UDS-b) interventions (Eugeni et al., 2024a). These interventions aimed to expand the size of emergency assembly areas, reduce evacuation times, and eliminate spatial obstacles hindering pedestrian flow. The obstacles identified included both direct factors—such as staircases, steep slopes, damaged or uneven surfaces, parked vehicles, and bulky urban furniture—and indirect factors, such as dead-end alleys or constrained pathways, as highlighted in previous literature (Bramerini & Castanetto, 2016; Alkassabany et al., 2018; Murao, 2008; Bernardini et al., 2021; Hosseini et al., 2009; Wang et al., 2022).

The urban design interventions primarily consisted of removing fences and enclosures, relocating parking areas, and increasing the share of

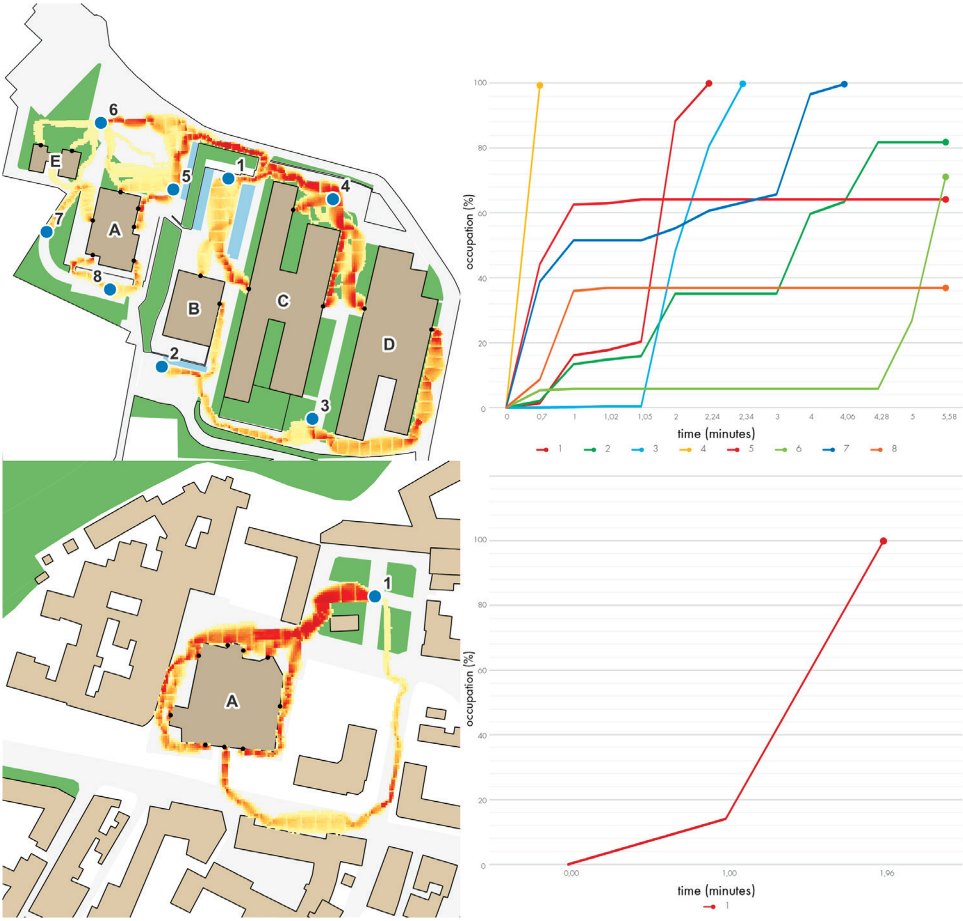

Figura 1 - *Scenario 1 (safety-optimazed spatial configuration) for the three university campuses (elaboration by authors)*

permeable green space (Figure 2). In the case of the Coppito campus, these strategies proved effective: 100% of the agents were able to reach emergency assembly areas, and the total evacuation time was reduced by approximately three minutes. Additionally, the overall extent of accessible open space for users increased. The same design strategies were applied to the Humanities campus, though with less significant impact. Despite a partial conversion of parking space into emergency assembly area, the total surface area remained insufficient to accommodate the simulated number of evacuees, resulting in minimal improvement over the baseline scenario. The boundary conditions adopted for Scenario 1—including the expanded area of the emergency zones as a result of UDS-b applications—are summarized in Table 2.

Table 2 - *Scenario 1 contour conditions after UDS-b application (elaboration by authors)*

Campus	Edificio	Maximum capacity	Emergency assembly areas	Maximum capacity
Coppito - STEM disciplines	A	1093	1	791
	B	300	2	427
	C	1458	3	473
	D	1344	4	437
	E	50	5	1060
			6	824
			7	493
			8	567
Historic centre - Human sciences	A	1766	1	1300

Conclusions

The research presented in this paper illustrates the potential of simulation-based approaches in supporting safety-conscious urban design, particularly within complex environments such as university campuses. Through the application of an agent-based methodology across three morphologically and contextually diverse case studies, the study has demonstrated how different spatial configurations influence the effectiveness of emergency evacuation strategies. The results obtained highlight three distinct conditions. The Roio campus, located in a purpose-built area with a balanced distribution of buildings and open spaces, represents a favorable condition in which the existing spatial layout is already capable of ensuring a complete and timely evacuation. This confirms the hypothesis that environments conceived with open space and circulation logic embedded into their design are more resilient under stress conditions (Fallah et al., 2014; Haghani & Sarvi, 2018). Conversely, the Coppito campus presents a partially critical scenario, in which the current configuration shows a gap between demand and available emergency space. However, the application of safety-oriented urban design techniques—such as the removal of barriers, reorganization of parking areas, and expansion of permeable open space—proved sufficient to close this gap and enhance both the evacuation time and spatial efficiency of the site. This reinforces the role of targeted design interventions in adapting existing configurations to perform more effectively in risk-prone contexts (Alkassabany et al., 2018; Hosseini et al., 2009; Wang et al., 2022). The most critical situation emerged at the Humanities campus in the historical center of L'Aquila. Here, the limited availability of open space and the rigid morphological constraints imposed by a stratified urban fabric significantly reduce the potential for design-based improvements. Despite the implementation of urban design interventions, the simulation results indicate that a large proportion of users remain without access to safe zones. This finding suggests that, in compact and historically layered urban contexts, emergency preparedness may require a shift from project-level interventions to broader strategic planning. Specifically, the identification and integration of additional emergency areas in the surrounding urban environment could offer a viable solution. This aligns with previous literature emphasizing that dense, heritage-based city cores often demand multiscalar and inter-institutional planning efforts to address risk comprehensively (León & March, 2016; Santibáñez, 2016).

Nevertheless, some limitations must be acknowledged. The absence of real-time behavioral data, such as that obtainable through mobile tracking or sensor-based systems, limits the context-specific accuracy of the model. Additionally, behavioral responses in panic conditions remain difficult to calibrate due to the scarcity of empirical observations, as noted in studies such as Simonov et al. (2018) and Wachtel et al. (2021). Despite these constraints, the methodology outlined here offers a structured and replicable framework for embedding simulation into the design process of safety-conscious public spaces. Its iterative and adaptive nature supports evidence-based decision-making and contributes to the development of urban forms capable of enhancing collective resilience in the face of emergencies. Overall, the study confirms the utility of agent-based simulation as a tool to inform urban design decisions under uncertainty. By enabling iterative testing of alternative configurations and measuring their impact through empirical indicators, the proposed methodology provides planners and decision-makers with a replicable framework for developing context-specific, performance-based strategies aimed at increasing the resilience of public spaces. Future research could extend the model to account for real-time data integration and multi-hazard scenarios, further reinforcing its applicability in dynamic and risk-sensitive urban contexts (Wachtel et al., 2021; Radianti et al., 2013).

Acknowledgements

The research described in this paper is part of three research projects in which the University of L'Aquila is involved as a partner: SICURA Project – "Intelligent house of technologies for safety - L'Aquila" - Emerging Technologies Support Programme (FSC 2014-2020) - Axis I "House of Emerging

Technologies", Research Programme: Safe City: urban design and technologies for urban safety; the National Centre for HPC, Big Data and Quantum Computing - PNRR Project, funded by the European Union - Next Generation EU; Territori Aperti, a centre for documentation, training and research for the reconstruction and recovery of disaster-affected fragile territories, funded by Fondo Territori Lavoro Conoscenza - CGIL CISL UIL.

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This volume explores the growing significance of open public spaces within university campuses—spaces that go far beyond their functional role to become essential arenas for social interaction, informal learning, well-being, and urban integration. Rooted in the research projects LOVE Sapienza and NARRATES both founded by Sapienza Università di Roma, and enriched by contributions from a 2025 international conference at DICEA-Sapienza University of Rome, this book provides guiding principles for designing open spaces that promote inclusion, health, and sustainability—on campus and beyond. Far from being passive backdrops, these environments shape the daily experiences of students, researchers, faculty, and visitors, offering settings that foster connection, creativity, and community. The book presents a critical reflection on how well-designed open spaces contribute to the quality of campus life and their evolving role as urban microcosms. It also examines how campuses can serve as active agents in urban regeneration and resilience, addressing environmental challenges through sustainable and adaptive design solutions. Structured around three interconnected themes—Campus and Public Spaces, Campus and University Communities, and Campus and the City—the volume gathers international best practices, offering an insightful tool for students, academics, designers, administrators, and urban thinkers.

Marichela Sepe is an Associate Professor of Urban Planning at DICEA, Sapienza University of Rome, and a member of the Academic Board of the PhD Program in Architecture and Urban Engineering. She also joined ISMed-CNR and DiARC-University Federico II. Sepe has been a Visiting Professor: in 2013 at Peking University, and in 2024 at the Faculty of Architecture of Gdańsk University of Technology. Her research interests include sustainable urban design, place identity, healthy cities, livable public spaces, creative urban regeneration, post-earthquake reconstruction and multi-adaptation, and cultural heritage enhancement. On these topics, she has published numerous articles in national and international journals, conference proceedings, books, and book chapters, and coordinated and served as the scientific director of national and international research projects. Since 2022 she is the Coordinator of the GUDesign network. Sepe serves as the Vice President of the Campania section of the INU (National Institute of Urban Planning) and is a member of the National Board of Directors of INU, the Board of Directors of EURA (European Urban Research Association), and the Urban Design Group. From 2014 to 2023, she has won several awards, including the Ardito-Desio Prize for papers presented at the Ipsapa conferences in 2014, 2016, and 2018; the Urban Planning Literature Award of the National Institute of Urban Planning (INU) in 2014, 2015, and 2017; and the Horizon Europe Award in 2023. She has also participated in various architecture and urban design competitions, achieving two first places and one selection.

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Copenhagen: detail of the Søndre Campus (photo by Marichela Sepe)

Formato digitale
ISBN: 978-88-7603-269-1 (e-Book) €. 0,00
Open access http://www.inuedizioni.com