# Visibility Graph Analysis vs. Human Mobility Patterns: An Empirical Validation of Simulation-Based Analysis Using Space Syntax in Public Squares

Reza Askarizad[1,2] and Chiara Garau[1(✉)]

[1] Department of Civil and Environmental Engineering and Architecture (DICAAR), University of Cagliari, Via Marengo 2, 09123 Cagliari, Italy
cgarau@unica.it

[2] Department of Urban and Regional Planning, Universidad Politécnica de Madrid, 28040 Madrid, Spain

**Abstract.** In recent decades, computational analytical approaches have revolutionised research in urban planning and design, offering new insights that traditional approaches omitted. Combining social science approaches with cutting-edge digital technologies, these developments help to simulate and forecast human behaviour in urban public places. Among them, Space Syntax constitutes a substantial framework; Visibility Graph Analysis (VGA) serves as an important tool for investigating socio-behavioural dynamics in the urban planning process. However, enquiries concerning the empirical validity of these simulations remain a critical issue. This work intends to expand the dialogue on validating simulation-based results using empirical research. It particularly scrutinises how agent-based simulations, guided by VGA's parameters, match observable human movement and socio-behavioural activities. The case study is "Bastione di Saint Remy", a historically and socially important urban square in Cagliari, Italy, noted for its energetic pedestrian bustle and attractive setting. This study aims to validate simulation tools by comparing agent-based simulation results with real-world mobility patterns, thus addressing gaps in their applicability and reliability. The methodology employs Space Syntax principles, utilising Depthmap software to conduct simulations, while human mobility patterns are analysed through systematic empirical observations. Although visual integration and visual connectivity show partial alignment with observed pedestrian movement, visual control and the visual clustering coefficient indicate a stronger correlation with human mobility and static behaviours. Furthermore, the study reveals underused areas within the square, therefore emphasising the necessity of further research on activating leftover spaces.

This paper is the result of the joint work of the authors. 'Abstract', 'Study Area', 'Methodology' and 'Results' were written jointly by the authors. RA wrote 'Agent-based simulation using space syntax' and 'Discussion and Conclusion'. CG wrote 'Introduction' and 'Human mobility patterns in urban public spaces'. CG coordinated and supervised the paper.

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O. Gervasi et al. (Eds.): ICCSA 2025 Workshops, LNCS 15896, pp. 51–68, 2026.
https://doi.org/10.1007/978-3-031-97654-4_4

**Keywords:** Visibility Graph Analysis (VGA) · Space Syntax · Social activities · Human mobility · Movement patterns · Urban squares · Urban public spaces · Computational design · Bastione di Saint Remy

## 1 Introduction

Designing socially sustainable urban spaces depends critically on an awareness of and managing human movement patterns, especially in public squares where many events and interactions comply with [1–3]. These spaces serve as vital nodes within the urban fabric, facilitating pedestrian movement, social exchange, and architectural expression [4, 5]. People's movement through and within public squares greatly affects their capability to support dynamic socio-behavioural activities [6, 7], accessibility, and usability. Good control of human movement patterns guarantees that these areas are not only efficient but also socially viable and equitable, therefore promoting a balanced cohabitation of many user groups [8–11]. The spatial configuration of urban squares plays a critical role in shaping how individuals navigate and interact within them, highlighting the need for strategies that harmonise mobility with the socio-functional objectives of urban design [12]. Responding to these challenges, urban planners can design public spaces that improve connectivity, promote active participation, and foster the growth of liveable cities [13, 14]. Smart urban systems that enable computational analytical methods to have changed the discipline of urban planning and design significantly over the recent years, and innovative tools that study and predict human behaviour in complex urban environments will contribute to the transformation of this discipline [15, 16]. These methods enable planners and designers to simulate and analyse spatial configurations and their influence on mobility and social interactions, thus providing data-driven insights which are typically absent from traditional approaches [17–19]. Simulation-based studies such as Space Syntax are among the most prominent given their ability to reveal important interactions between human movement patterns and spatial layout [20–22]. The visual narrative of the flow of pedestrian movement in the urban environment can contribute to understanding people's mobility and urban activities, particularly those functions related to urban public spaces [23]. In this regard, one of the key features of Space Syntax, the Visibility Graph Analysis (VGA) has proven to be useful in examining human behaviour through the visual connection within urban spaces [24, 25]. This analytical approach permits the identification of potential hotspots, areas of significant pedestrian flow, and locations encouraging social interaction [26]. Expanding on these capabilities, Agent-Based Analysis simulates individual decision-making processes where agents reflect more fine-grained understanding of pedestrian movement patterns [27–29]. This approach gives valuable insights about how people move in urban environments, also how mobility patterns may change, and how they react to design interventions, by modelling the behaviours and interactions of virtual agents [30, 31] within a spatial framework. This new style of synthesis which is made possible by computational methods marks an important paradigm-based shift toward effective and responsive urban-drawing devices on-site, specifically in lively urban squares.

The evolution of computational simulation tools used for urban planning has witnessed exciting developments and widespread implementation even if doubts over their

validity and reliability continue to be a pressing concern. While approaches such as agent-based analysis offer useful predictions about human mobility patterns, their results often lack empirical validation. This raises critical issues about how real are simulation-based outcomes with measures in real settings, especially when considering dynamic contexts such as public squares. In the absence of experimental evidence that can reflect the reality in urban form, results achieved from simulation are likely to yield fragmentary or even incorrect lessons and therefore be of little use as a practical mechanism in urban design. This gap highlights the importance of systematic contrasts between simulation-based analyses and actual patterns of human mobility. Agent-Based Analysis, a subset of VGA, can potentially address this problem by simulating the choices of individuals as they play the game of mobility. However, its performance in adequately depicting real-world dynamics is still restricted sampling. As computational tools have the potential to influence urban design practices in social sustainability goals, closing this gap is essential to improve their reliability and effectiveness.

This study focuses on the possible empirical validity of simulation-driven examination, specifically Agent Based Analysis within Space syntax, based on its performative congruence with real human mobilities and socio-behavioural activities observed in public squares. The study addresses two fundamental key questions: (1) How successfully does Agent-Based Analysis replicate real-world human movement? (2) How can employing this sort of simulation-based analyses inform socially sustainable urban design? On these questions, the research poses two hypotheses, (a) Agent-Based Analysis may effectively replicate real-world mobility patterns when spatial configurations are a primary determinant of movement, and (b) incorporating validated simulation tools into urban design processes could improve public squares in terms of functionality. In linking computational simulations with empirical observations, this work deepens the understanding of human behaviour in urban space.

The findings are expected to advance the application of simulation-based methodologies, offering meaningful guidance for urban designers, planners, and architects to create dynamic and socially engaging public environments.

## 2 Literature Review

### 2.1 Human Mobility Patterns in Urban Public Spaces

Human mobility patterns in urban public spaces have attracted considerable research interest due to their relevance in urban planning, transportation, and social behaviour analysis. One of the earlier studies by Jahromi et al. [32] conducted a simulation model using call detail data, GPS, and WiFi traces to analyse human mobility. Their findings revealed that the simulator is highly adaptable and effective at modelling spatio-temporal behaviour across different geographic and population scales. This adaptability underscores the potential of technology in understanding urban mobility and its integration with urban systems. However, these models face limitations in providing real-time data accuracy and capturing the complexity of social dynamics in urban environments.

Sun et al. [33] argued that urban dynamics are both predictable and stable, making them critical for forecasting urban behaviour and detecting anomalies. They contended that stable urban dynamics may enhance traffic management and planning. Yang et al.

[34] extended this idea by establishing a clear correlation between mobility behaviours and urban functional areas, emphasising the importance of spatial analysis for optimising urban planning. Nonetheless, these models often overlook the potential disruption of previously stable mobility patterns caused in urban forms, or the integration of mixed-use spaces. Kang et al. [35] highlighted the role of urban morphology in shaping mobility, suggesting that urban design significantly influences how people move through space. This perspective is confirmed by Santilli et al. [36], who demonstrated that hybrid forecasting models can accurately estimate pedestrian flows. While these models contribute significantly to planning, they may not fully capture the impact of emerging urban forms and newer mobility options.

The integration of sustainable mobility practices has also become a focal point in urban mobility studies. Sultan et al. [37] examined factors influencing mobility mode choice, revealing that barriers to adopting sustainable mobility remain despite infrastructure improvements. Their work emphasises the need for targeted planning to address those barriers. Mezoued et al. [38] adapted the Slow City concept to larger cities, with an emphasis on walking as a main transport mode. Adapting this model is essential for promoting sustainable mobility in densely populated urban areas. Nonetheless, a struggle exists in addressing the balance between pedestrian-centric areas as well as other urban transportation modes, especially micro-mobility vehicles, which Zhang et al. can pose challenges to road safety [39] noted. It's a contradiction in urban mobility planning, where expanding space for some modes of transportation is creating risks for others. Another important element of human mobility in urban areas is safety. Campisi et al. [40] noted that pedestrian safety is determined by many different factors including overall crossing patterns, quality of the infrastructure and traffic conditions. Their analysis showed that distracted pedestrians that use mobile phones were more prone to accidents, highlighting a critical issue in urban mobility. Although Bluetooth networks are a technological advancement for analysing pedestrian movement, the application of such technologies is ineffective in real-world settings despite their utility [41]. These advancements provide valuable insights but also highlight their weaknesses of relying solely on technological solutions without addressing broader social and infrastructural factors.

The built environment significantly influences human mobility, and numerous studies emphasised the important role of spatial configuration, land-use diversity, and urban attractiveness in the movement patterns. Yang et al. [42] contended that the residential built environment is as important—even, perhaps, more so—than the distance travelled or the number of stops in shaping human mobility. These insights highlight the role of urban design in promoting social interactions and improving urban quality of life. Zhang & Li [43] proposed an Activity Space-based Gravity model, which modelled the spatial temporal characteristics and the attractiveness of each urban region, significantly enhancing the prediction of human mobility flows. This advancement is a significant step towards more precise and efficient urban mobility models. Khotbehsara et al. [44] revealed that while in more urbanised regions other factors may play, urban land-use diversity and compatibility distinctly shape pedestrian mobility in low-density city environments.

However, despite these advancements, Chu et al. [45] suggest that existing models still struggle with issues of socio-economic segregation. Abbiasov et al. [46] found that despite the benefits of increasing access to local amenities on human mobility, it also often increases segregation, especially low-income residents, which may prove problematic for the large-scale adoption of concepts such as the 15-minute city. Indeed, this results in an important shortcoming of current research that tends to emphasise accessibility as a main imperative of urban mobility, while neglecting the influence of socio-economic disparities on mobility patterns and access to urban facilities.

In a nutshell, while substantial progress has been made in understanding human mobility patterns, a limited number of studies have integrated space syntax analysis or investigated the validity of agent-based models in this field. Despite the wide range of studies undertaken, there is a continued need for more comprehensive research that bridges the gap between spatial design, human behaviour, and socio-economic dynamics in urban mobility studies. The following subsection will evaluate such studies primarily focused on agent-based simulations using space syntax.

### 2.2 Agent-Based Simulation Using Space Syntax

Agent-based simulation, particularly when combined with space syntax, has become an effective tool for analysing human movement and behaviour in urban environments. This subsection summarises relevant research, discussing the benefits and drawbacks of combining these methodologies for understanding the relationship between spatial configuration and user movement patterns. Esposito et al. [47] demonstrated significant relationships between experimental approaches to spatial cognition and predictions based on space syntax, suggesting that the respective approaches may complement each other and collectively better inform our understanding of agent-based decisions and behaviours. Omer and Kaplan [48] stressed the usefulness of agent-based pedestrian volume models in an integrated space syntax framework, specifically in contexts with inconsistent correlations between street network and land-use patterns. This underlines why using agent-based models has the potential to address gaps in traditional space syntax approaches, particularly as they relate to evolving urban conditions.

In addition, Mara et al. [49] showed how, by integrating metrics from space syntax with agent-based modelling, the interactions between pedestrian behaviour, urban configurations, and environmental conditions can elucidate crime distributions. This approach highlights the flexibility of agent-based models across a wide range of use cases, such as pedestrian behaviours and crime reduction. Koutsolampros and Varoudis [50] proposed a hybrid model that includes non-player-character movement techniques leads to simulations behaving more “human-like” and follow realistic movement patterns. This is an advancement as a common critique of traditional space syntax model is that they fail to emulate nuanced human behaviour within complex spatial environments.

However, challenges still exist despite these advances. Chun et al. [51] conducted no statistically significant correlations between eco psychology theories, agent-based modelling and observed human behaviour. It highlights the complexity of spatial usage patterns for humans, and the difficulty in modelling them correctly.

Conversely, Tang and Hu [52] showed that agent-based simulations can be used to identify optimal pedestrian flow in urban spaces in a way that affords optimised

access to public space which implies that these models can still provide value in process application especially in relevant urban contexts. Furthermore, research has illustrated how urban facility design shapes human mobility patterns and static social behaviours in public space. Such a configuration would create greater socially inclusive urban public spaces as incorporating more of visual connectivity and integration (with a reduced visual entropy and less visual cluster) and therefore offers more of urban vitality perspective [53].

Further research has investigated innovative approaches to agent-based modelling. For example, Yıldız and Çağdaş [54] calculated the attractiveness value of the urban space components based on their distance from the reference point and the attraction factor of the use, showing the effectiveness of this method in simulating temporal variations in user behaviour in public squares. Sobreira [55] also presented a simulation of inner-city squatter settlements demonstrating the ability of agent-based models to depict complicated urban systems, e.g. the role of the abundance of vacant land and the interactions of inhabitants. Turner and Penn [56] further enrich this discourse. They found that human movement could rather be fit well by a very simple movement rule based on a "random next step" that is influenced by the visual field at that location, and outperforms models based on destination. This is in line with Jiang and Jia's [57] conclusion on aggregating flow patterns being more influenced by configurations of the street network, as opposed to specific (and relatively natural) human behaviours, highlighting the primacy of spatial affordances in activating movement.

In contrast, Mohammed and Ukai [58] employed other spatial metrics like the space matrix and mixed-use index within agent-based models, offering urban planners a generalized tool to forecast urban land expansion. This highlights the possibilities of agent-based modelling as a bridge between spatial analysis and applied urban planning. The use of agent-based models in tourism and smart city applications opens further opportunities for these models. Wang et al. [59] used 3D isovist analysis alongside agent-based modelling to predict visitor flow volumes in tourism-oriented villages, offering implications toward optimising visitor behaviour. With the same view, researchers [60] investigated the application of smart city initiatives in the sector of urban architecture in order to improve pedestrian movement in separated urban zones as a solution for some constraints of traditional urban compositions.

Despite the significant advancements in integrating space syntax with agent-based modelling, a gap remains in empirically validating these simulations against real-world human mobility patterns. While a limited number of studies emphasise the accuracy of agent-based models in replicating observed behaviours, others highlight discrepancies that suggest the need for further refinement. This research addresses these gaps by empirically validating simulation-based analyses in a renowned public square of Cagliari in Italy, through a comparison with actual human mobility patterns. This study aims to provide a framework for evaluating and validating the effectiveness of agent-based simulations in urban planning by examining their interaction with real-world human mobility patterns, thereby enhancing the design of user-centric public spaces. Figure 1 illustrates a summary of the conducted literature review.

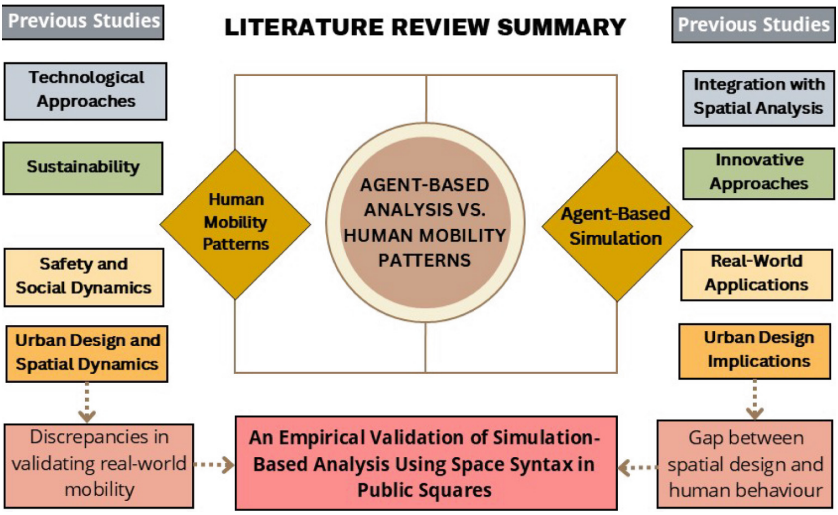


**Fig. 1.** Main themes and findings of the literature review, with the existing gap covered with this study.

## 3 Methodology

This study adopted a mixed-methods research strategy, integrating both quantitative and qualitative approaches. The quantitative aspect involves the simulation of spatial configurations using Space Syntax analysis. For this purpose, the authors used UCL Depthmap 10 software. Before conducting the syntactical analysis, a detailed urban map of the studied square was meticulously drawn to include all relevant elements and urban amenities that might influence the simulation of human mobility patterns.

This included both natural and artificial features, such as gardens, trees, lamp posts, seating areas, and other types of urban furniture, all of which were drawn using AutoCAD 10 software. The map was exported to DXF format and imported into Depthmap software for analysis. There were two main procedures in the analysis of spatial configuration: visual graph analysis (VGA) to evaluate the square's spatial attributes and an agent-based analysis that questioned the individual movements based on the environment's spatial configuration.

The analysis employed several VGA metrics to understand the square's visual structure and its influence on movement. Visual integration reveals how easily a space can be seen from all others, suggesting areas of higher usage. Visual connectivity counts direct sightlines, indicating immediate visual and, consequently, spatial access. The visual clustering coefficient shows how stable or disrupted the view is during movement, potentially identifying pause points. Visual control quantifies the ability to see and be seen, hinting at informal surveillance. Finally, gate count identifies locations where many potential paths converge, likely attracting spontaneous pedestrian flow [61, 62].

The qualitative phase involved empirical observations of how humans moved in the square to validate and ground-truth the agent-based simulations. The observations sought to measure the degree to which simulation results matched the actual pedestrian motion

of the individuals found at the public square. In this study, static snapshots techniques are used as the adopted observational method. In order to analyse a broad understanding of human movement patterns a series of snapshots were taken from the top floor level. To ensure that external factors did not make an impact on this experiment, observations were done under good weather conditions. Lastly, a comparative analysis was undertaken to compare the agent-based simulations conducted in the Space Syntax framework with real-world data observed. Figure 2 shows the paradigm for the research methodology used in this study.

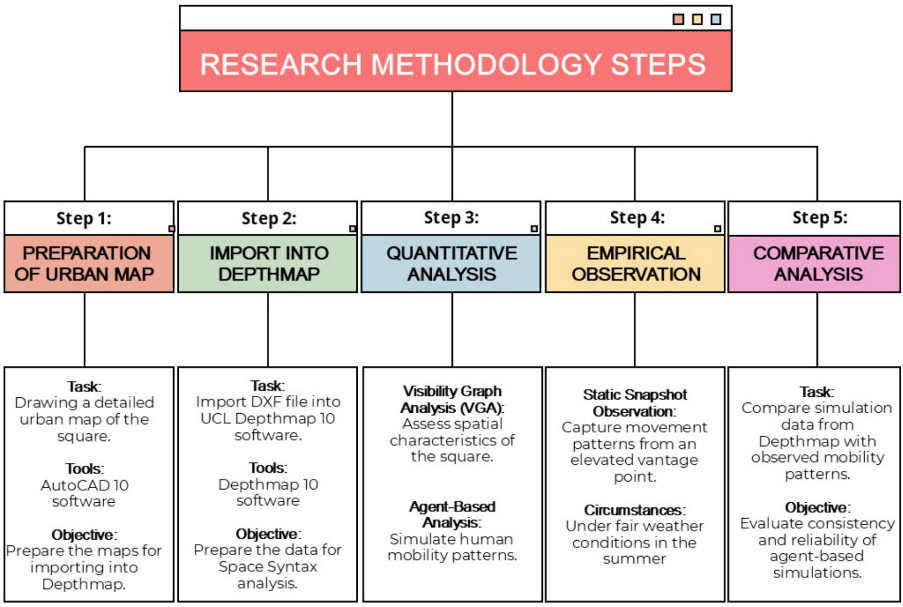


**Fig. 2.** Flowchart of research methodology illustrating the sequential steps from spatial configuration analysis to empirical validation.

## 4 The Area of Study: the "Bastione di Saint Remy"

The "Bastione di Saint Remy" is located in Cagliari, the capital of Sardinia, Italy (Fig. 3). Sardinia is known for its cultural heritage, traditional architecture, and natural beauty, and it has great importance in national and international tourism. Located in the historical Castello district, the "Bastione di Saint Remy" has a central location in Cagliari, boasting a strategic point of the city and the Gulf of Cagliari. The great Bastione di Saint Remy is a high monumental structure and urban square, built in the late 19th and early 20th centuries. It has grand arches, white limestone facades and an imposing staircase leading visitor up to an elevated terrace, all characteristics of neoclassical architecture. The structure is named after a notable figure from the time it was built, Baron Saint Remy. This landmark of architecture was once built to protect the city but has since been converted into a public space and a social center.




**Fig. 3.** Geographical location of the case study (a: Location of Sardinia in Italy; b: Location of Cagliari Metropolitan City in Sardinia; c: Location of Study Area in Cagliari; d: Location of Castello Neighbourhood in Cagliari; e: Location of Case Study in Castello Neighbourhood; f, g, h: Different views of Bastione di Saint Remy).

The square is an essential component of Cagliari's urban fabric, connecting the lower city to the Castello district. It is reached by a series of broad staircases (with elevators); it conduits pedestrian activity. At its highest point, the Bastione forms a large open terrace, a public gathering space.

Its panoramic views encompass the city, the harbour, and the surrounding hills, creating an unparalleled setting for both locals and visitors to enjoy. The Bastione is one of the most important tourist venues, and it is visited by many different people for its significance, architectural style, and lively atmosphere. It is an important place for cultural gatherings, markets, and social meetings. Particularly well-known for its magnificent views, it makes for an optimal place to observe both sunrise and sunset. It is best known for the relaxed nature, availability of cafes and seats, and as such is a warm place to socialise.

Due to being a historical monument, urban square, and social space, the Bastione di Saint Remy provides an ideal case study for this research. Its prominent location in Cagliari guarantees a great variety of users (both tourists and local residents) and is an interesting context for the study of the patterns of human mobility and social activities.

The square is an interesting location for studying the relationship between spatial configuration and human mobility as it possesses unique architectural features and is part of the urban environment surrounding it. Moreover, its identity as a placemaking and touristic site is consistent with the research aim of exploring how city design impacts where we play (stationary social activities) or go (movement of beings) in public places. Through empirical-led analysis by taking the Bastione di Saint Remy as a centre point, this study seeks to explore the everyday experiences and visions of those that shape the space. This data will then serve to verify whether simulated analysis predicts actual user mobility patterns and preferences.

## 5 Results

The obtained results are categorised into two main sections: empirical observations and Space Syntax analysis, along with their overlapping outcomes to assess the level of consistency between the two datasets. The empirical observations were conducted in July 2024. Based on the investigations and observations, the square experiences its highest pedestrian mobility around sunset. Consequently, the observations occurred between 8:00 p.m. and 9:00 p.m.

The method used for documenting behavioural maps in this study is based on the accumulation of crowds, which has been visualised using a black-coloured chromatic spectrum. In this visualisation, areas with higher pedestrian density are represented in darker black, while areas with lower density appear in lighter shades. In the Space Syntax analysis, various VGA metrics were employed to provide a comprehensive assessment of influential spatial factors. These metrics include visual integration, visual connectivity, visual clustering coefficient, visual control, and gate count analysis. In these visualisations, areas with higher numerical values are represented in warmer colours, while areas with quantitative values appear in cooler colours.

The findings from the VGA analysis at Bastione di Saint Remy indicate that visual integration is somewhat correlated with observed pedestrian mobility patterns. The highest integration value in this analysis was 19.57, recorded in front of the entrance stairs. While this value demonstrates a high level of consistency with observed mobility patterns, it also highlights additional potential spaces that could facilitate pedestrian movement (Fig. 4). Similarly, the visibility graph of connectivity yields comparable results, with the highest connectivity value reaching 4761, suggesting a moderate consistency with pedestrian mobility patterns (Fig. 5).

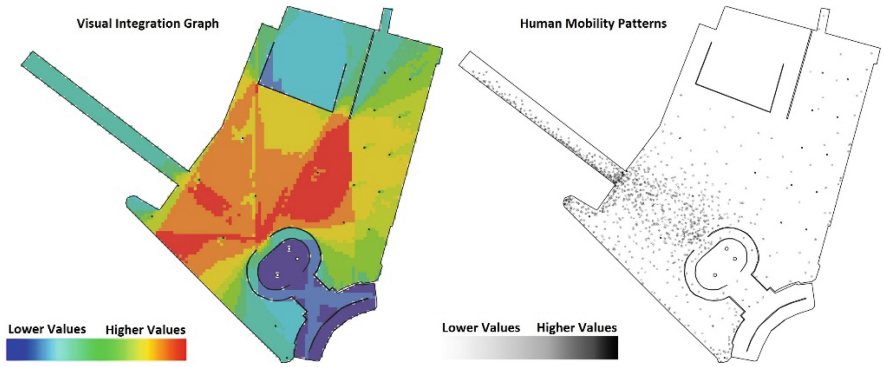


**Fig. 4.** Visual integration analysis of the study area and its comparison with human mobility patterns.

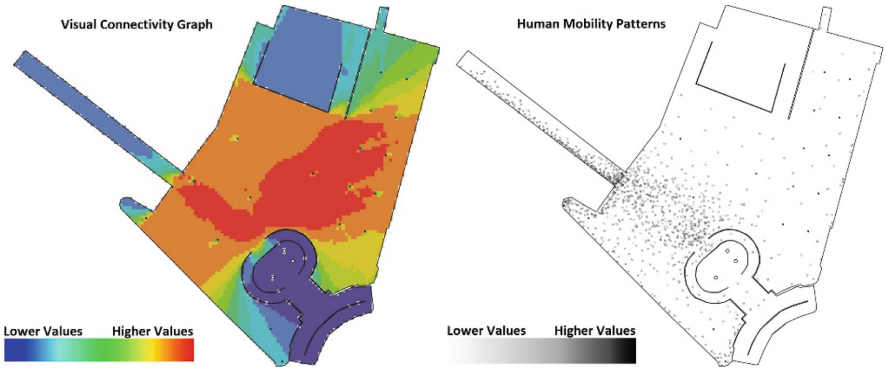


**Fig. 5.** Visual connectivity analysis of the study area and its comparison with human mobility patterns.

While integration and connectivity exhibited partial consistency with observed movement patterns, other variables—such as visual control and visual clustering coefficient—displayed greater alignment between the simulated models and real-world pedestrian behaviour. The results of visual control analysis indicate a significant correlation with observed pedestrian movement patterns, with the highest visual control value recorded at 1.68, validating the movement patterns within this public space (Fig. 6). Additionally, the visual clustering coefficient showed a high degree of correlation with stationary behaviours, with the highest quantitative value of 0.98 (Fig. 7). Notably, the gate count analysis—conducted using the agent-based tools of the software—revealed a complete inconsistency between the simulation results and the actual observed movement patterns within the public square (Fig. 8).

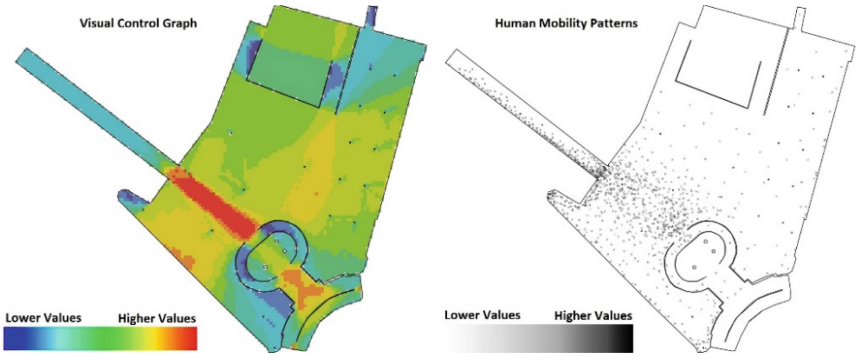


**Fig. 6.** Visual control analysis of the study area and its comparison with human mobility patterns.

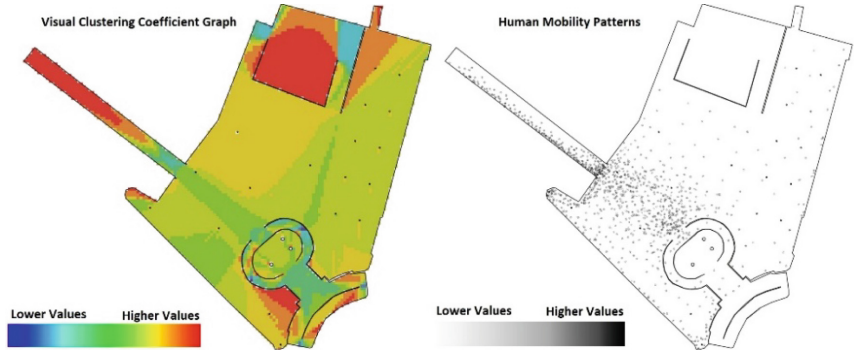


**Fig. 7.** Visual clustering coefficient analysis of the study area and its comparison with human mobility patterns.

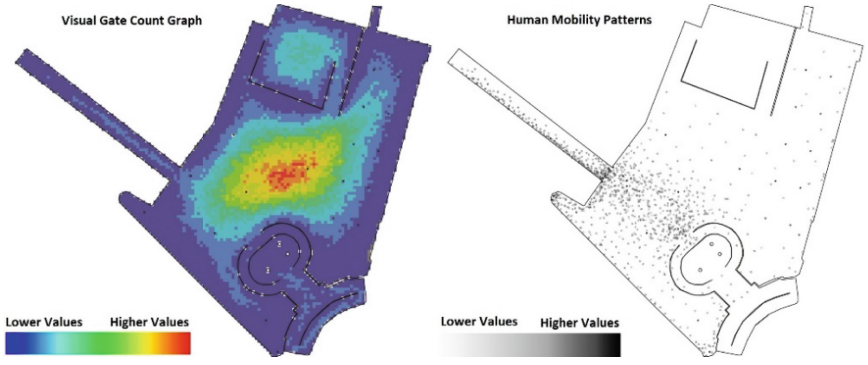


**Fig. 8.** Visual gate count analysis of the study area and its comparison with human mobility patterns.

## 6 Discussion and Conclusion

This study explores the viability of simulation-based approaches in predicting human mobility behaviours in real-life environments; it tests the empirical adequacy of these models in the field of Space Syntax, especially the agent-based analysis, at public squares i.e. a representative case study for geo-spatial settings. This relationship is also key to evaluate the accuracy of computational predictive models of the urban processes in urban studies and their applicability to provide relevant insights on evidence-based urban design.

The findings obtained shows that human mobility patterns follow spatial configuration and its topological relationships to some extent. Strikingly, the visual control showed great correlation with pedestrian flow patterns, supporting the theory of Jan Gehl [63] not only should urban spaces be designed in a way where we can see them, they should also promote the value of being seen by others. Finally, it was found that the visual clustering coefficient was highly correlated with stationary behaviours, suggesting that the metric has notable significance for socio-behavioural evaluations of public spaces. Conversely, the presence of the visual integration and connectivity metrics does not fully reflect human mobility trajectories, although some residual/unused spaces have been pin-pointed in the square and suggest more works on residual spaces and their activation in future studies.

Despite these insights, certain limitations should be acknowledged. Firstly, the study focuses on a single case study—Bastione di Saint Remy—meaning that the findings are intrinsically tied to its specific spatial and social context. Thus, dimensions such as functional characteristics, aesthetic experience, and daily activity rhythms might also affect pedestrian mobility besides the shape of the space itself. In addition, the observed data collection was limited to a specific time interval, which may not be entirely representative of the overall mobility pattern taking place within the study area. Future research should explore these elements in greater detail and consider other urban squares to improve the generalisability of the findings. Additionally, methods like ethnographic studies and participatory observations can help us better understand how users engage with public spaces.

The originality of this research is highlighted when comparing these results with prior studies. Whereas other studies demonstrated the contribution of visual integration and connectivity to pedestrian movement prediction [64–66], this study demonstrates that visual control and clustering coefficients may offer greater predictive power for socio-behavioural activities in certain public spaces. This distinction highlights the importance of context-specific analyses and the importance of methodological refinement in Space Syntax studies.

In conclusion, this work turns directly to the two substantive research questions. Firstly, it shows that Agent-Based Analysis based on Space Syntax has some degree of internal validation of real-life human movement patterns, where some metrics (such as visual control, clustering coefficient, integration, and connection) are better classifiers than others. Second, findings showing the effects of space use simulation analyses in urban use finding processes can help to achieve socially sustainable public space in such as areas with high activity and those that are not sufficiently activated urban settings. Further studies should extend these findings by improving simulation models and

incorporating in particular further socio-spatial variables in order to develop predictive accuracy and practical application.

**Acknowledgments.** This study was supported by the MUR through two projects, (1) SMART3R-FLITS: SMART Transport for Travelers and Freight Logistics Integration Towards Sustainability" (Project protocol: 2022J38SR9; CUP Code: F53D23005630006) and (2) MOVING StEPS: MOVING from Street Experiments to adaptive Planned Solutions (Project protocol: 2022BLK9TS; CUP Code: F53D23005550006), both financed by the PRIN 2022 (Research Projects of National Relevance) program, funded by the European Union (NextGenerationEU). This study reflects only the authors' views and opinions, and neither the European Union nor the European Commission can be considered responsible for them.

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