Simulation to Forecast Crime Patterns: comparing Space Syntax and Agent-based Models in exploring pedestrian movement and visibility.

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Abstract

Space Syntax comprises a set of techniques that emphasize both material and immaterial characteristics of urban space. However, its inherent lack of a time component and land-use variables limits its effectiveness in investigating crime dynamics at the micro-urban scale. On the other hand, ABMs are simulations of interacting agents capable of perceiving their environment, influencing each other, and making autonomous decisions without central control, whose behaviour depends on time and environmental components. Nonetheless, ABMs face challenges in terms of the required amount of input data and model transparency, as well as regards the matter of validation. Despite being based on different modelling approaches – embodying the top-down versus bottom-up contraposition – both Space Syntax and ABMs can qualitatively and quantitatively analyse crucial components for crime analysis, such as flows, copresence, and visibility, deemed key aspects underlying the crime opportunity concept. This paper establishes a bridge between Space Syntax and ABM through the study of crime in urban settings, scrutinising the fundamental metrics that can significantly contribute to the identification of high-risk locations—specifically, pedestrian flow and visibility. It presents two new models, respectively using Space Syntax methods and ABM, applied to two separate case studies in the historic city centre of Pisa, Italy. It has three objectives: first, to compare the diverse outcomes the distinct approaches provide in terms of people flow and visibility estimation in the built environment; second, to discuss their potential in forecasting risky areas; and, lastly, to propose an integration between Space Syntax metrics for movement within ABMs as parameters to guide agents' movement. In essence, this study proposes a methodology oriented towards creating a model capable of simulating the relations between people's behaviour, urban configuration, environmental conditions, and crime distribution, thereby representing a useful decision-support tool for crime prevention purposes and for broadly exploring and modelling pedestrian behaviour.

Keywords: agent-based modelling, space syntax, pedestrian movement, visibility, crime, risky places.

1. Introduction

The demand for efficient **urban simulation** tailored for city environments has attracted significant attention from both academics and practitioners over the last decade, given the increasing complexity involved in the transformation's prospects provided by the emerging smart cities and their frameworks. However, in urban planning, this line of inquiry and experimentation is rather recent. It is motivated by the need for merging different spatial knowledges and to use them in conjunction with the representation of socio-economic dynamics that happen within the city (Batty, 2018).

Despite improvements in computational methods to territorialize variables following the diffusion of Geographic Information Systems (GIS) in urban planning, there are still issues linked to how to associate different cityscape characteristics, such as urban form and individuals' actions and behaviours. It must be acknowledged that an urban simulation will not be an "identical twin" (Batty, 2018), especially when considering the entire city as a self-organized process. Merging ever-changing social and economic processes with built-structures and natural environments affected by those dynamics requires a comprehensive-reiterative method yet to be developed. One of the fundamental dynamics to be explored in urban environments is movement, which is related to the spatial configuration (Hillier, 2007). Movement pertains to agents' routing habits, certain patterns of social interaction, the placement of urban equipment and economic activities, and urban liveability (Van Nes et al., 2016). Moreover, movement dynamics, and by extension, the environment – including factors such as the layout of streets, lighting, and the level of surveillance – are closely related to crime activities (Jacobs, 1961). Understanding the relations between these factors is crucial for elaborating accurate models and safe environments accordingly.

From the criminological standpoint, the significance of the environment is widely recognised. Beginning with the influential research of the School of Chicago, passing through the contributions of Lynch, Woods, Jacobs, and Angel, and extending to the ones of prominent scholars like Jeffery and Newman – just to name a few pioneers – the **environmental approach to security** has emerged as a viable alternative to traditional and social perspectives. The central idea is that the environment, considered in both its spatial and situational dimensions, plays a crucial role in understanding the dynamics of crime and fear of crime (Weisburd et al., 2012; Mara and Cutini, 2024). Indeed, the environmental approach to security constitutes a multidisciplinary framework that encompasses environmental criminology, urban planning, architecture, psychology, and various other disciplines. This approach aims to uncover behavioural theories capable of elucidating the logic and elements leading to criminal events. By dissecting it into microelements, the goal is to facilitate the identification of targeted interventions to disrupt the chain of events that culminate in criminal acts. The strands highlighted by Wortley and Townsley (2017) encompass the realms of 'designing out crime', 'situational crime prevention', 'crime patterns investigation', and 'crime prevention through policing', of which the rational choice theory and the crime triangle constitute two cornerstones. In general, through the integration of these strands, crucial approaches and tools for understanding criminal dynamics emerge.

From a methodological standpoint, the recent strides in digital technology have profoundly enhanced computational capabilities, pushing the boundaries of achievable complexity – see, for example, the developments in the field of digital twins (Wan et al 2023) and city digital twins specifically (Papyshev and Yarime, 2021). Notably, **two distinct modelling approaches stand out: the top-down approach and the bottom-up approach**. The top-down approach excels in extracting the macroscopic behaviour of a system, unveiling the big picture and key drivers through the analysis of aggregated datasets and substantial abstraction and simplification. This makes it particularly valuable when dealing with highly homogeneous samples and 'stationary' conditions. On the other hand, the bottom-up approach is well-suited for capturing high complexity – demanding extensive input datasets – by defining agents *ab initio*, detailing their fundamental behaviour, and establishing the governing laws of the environment under exam. In particular, it assumes a pivotal role in modelling heterogeneous elements in 'non-stationary' conditions. Two emblematic examples of these modelling approaches are Space Syntax analysis, representing the top-down approach, and Agent-Based Modelling, embodying the bottom-up approach.

Space Syntax (SS) encompasses both a theoretical framework and a suite of techniques and measures designed to unveil intrinsic spatial relationships and features through the configurational analysis of the built environment. It proves invaluable in investigating and interpreting social organisations and human behaviour within settlements (Hillier and Hanson, 1984; Van Nes and Yamu, 2021). Among the well-established applications of SS is the comprehension of the functioning and hierarchy of urban networks, achieved through assessments of to-movement and through-movement potentials. This methodology also facilitates the estimation of vehicular and pedestrian flows in urban areas, thereby enabling the assessment of complex phenomena like land use patterns, migration trends, and property price variations (Hillier et al., 2007; Yamu et al., 2021).

In the realm of estimating pedestrian flows, SS demonstrates an impressive capability, ranging from 50% to 80% in capturing the variance in pedestrian movement from one location to another (Penn and Turner, 2002; Hillier et al., 1993; Jiang, 2009; Penn et al., 1998). This suggests that pedestrian movement predominantly relies on variables representing street network properties (Jiang, 2009), with measures of axial choice, integration, and connectivity exhibiting the most robust correlations (Sharmin and Kamruzzaman, 2018). Moreover, a multitude of studies has underscored SS's proficiency in interpreting social dynamics in the realm of crime. Research has delved into the relationship between urban configuration and crime distribution, unveiling correlations between permeability, accessibility, connectivity, and crime (for a comprehensive review, refer to Mao et al., 2023). Notably, these studies implicitly draw upon environment-based crime prevention theories, seeking to fathom crime dynamics and establish parameters for identifying high-risk areas within the urban context through the interpretation of the urban network and the extraction of metrics related to movement and visibility. A critical consideration that emerges in the study of social phenomena using the configurational approach is the inherent challenge of incorporating the temporal component (Ericson et al., 2021).

On the other hand, **Agent-Based Modelling** (ABM) stands out as a computational modelling technique adept at simulating intricate spatial and non-spatial phenomena. It begins with a bottom-up approach, defining agents—each potentially unique in characteristics—and the environment wherein they interact. This methodology generates models that are capable of capturing emergent patterns and collective behaviour, given that each agent serves as an autonomous decision-maker. Moreover, its inherent multiscale nature, encompassing both spatial and temporal dimensions, facilitates a nuanced understanding of processes shaping social dynamics (Crooks et al., 2018; Esposito et al., 2020). ABM finds diverse applications in the social and geographical realms (see Crooks et al., 2018). Particularly within the domain of crime, ABM has demonstrated utility across various scenarios (Rosés et al., 2021; Malleson et al., 2013; Birks and Davies, 2017). Similar to SS, ABM reveals its capacity to encapsulate human behaviour and interpret analogous metrics related to movement and visibility, despite originating from distinct assumptions and logics. ABM excels in identifying unpredictable dynamics, albeit with the trade-off of necessitating extensive input datasets, increased computational load, and the risk for the 'black box' effect.

In the realm of **modelling and investigating social dynamics, the temporal component assumes a pivotal role**. The same physical space can serve various functions and be experienced differently based on factors such as the time of day, individual habits, urban equipment, and open commercial activities. Consequently, a model aimed at analysing the impact of the urban environment on crime dynamics at a granular scale must incorporate the ability to capture these nuanced elements, which SS fails to address. However, ABM lacks accurate models capable of capturing the influence of spatial form on wayfinding and pedestrian behaviour. This deficiency presents a challenge in establishing the 'laws' governing the model and makes the model a unique piece, (almost) only effective for the specific area and sub-system under investigation.

Building upon these assumptions, this study endeavours to **juxtapose two models tailored for investigating crime dynamics at the micro-urban scale**, utilizing distinct frameworks. The objective is to scrutinize fundamental metrics that can significantly contribute to the identification of high-risk locations—specifically, pedestrian flow and visibility (see Section 3). In particular, Section 2 introduces the case study, delineating its unique characteristics and the rationale behind its selection. Section 3 elaborates on the datasets constructed and employed in the study. Section 4 delineates the methodology, highlighting the choice of criminological interpretative theory, the techniques and the measures applied in the SS modelling, and the assumptions made in building the ABM. Advancing further, Section 5 presents the results by comparing the models in terms of pedestrian flows, visibility, and discussing the impact on crime risk. Moreover, it proposes a preliminary attempt of integration between the two modelling approaches. Section 6 briefly summarizes the primary findings, identifies critical aspects, and outlines potential directions for further development.

2. Case study

The case study is situated within the historical centre of Pisa, Italy. Currently, the city stands out for its vibrant university community, both in terms of demographic composition and widespread presence of academic hubs and buildings in the city centre (Fig. 1). In addition to this aspect, tourism plays a significant role.

Specifically, the study investigates two areas, both in the central portion of the historic core. Aimed at investigating the behavioural patterns at the micro-urban scale, the area of Piazza delle Vettovaglie and Via Ulisse Dini were chosen for their peculiarities (Fig. 1). They both are flat ~~It is a flat~~ pedestrian areas characterized by adaptability over both the long term (annual, seasonal, monthly timeframes) due to variations in the presence of student, tourist, and service components in the city, as well as over the short term (weekly, daily timeframes) due to different flows, environmental conditions and diverse visitors that characterize it at various times of the day. At the same time, the two case studies present some differences. The area of Piazza delle Vettovaglie is a commercial hub that undergoes a series of transformations throughout a single day: in the early morning, it serves as a thoroughfare and market area; transitioning into a hub for tourists or workers during the late morning and early afternoon; then evolving into a passage or stopover point in the evening. Ultimately, it transforms into the primary focal point for nightlife, especially during weekends. On the other hand, the area of Via Ulisse Dini does not host commercial activities, resulting in a much less variable physical and functional environment, with fewer time-dependent factors. Actually, this represents a more elementary case, geographically close and similar to the first one, yet quite different in certain other aspects (see Section 3) which make it suitable for observing the basic dynamics/functioning of both SS and ABM models. The geographical scope of the studied areas is equally wide-ranging, with each area spanning approximately 11,000 square meters (105*105 sqm).

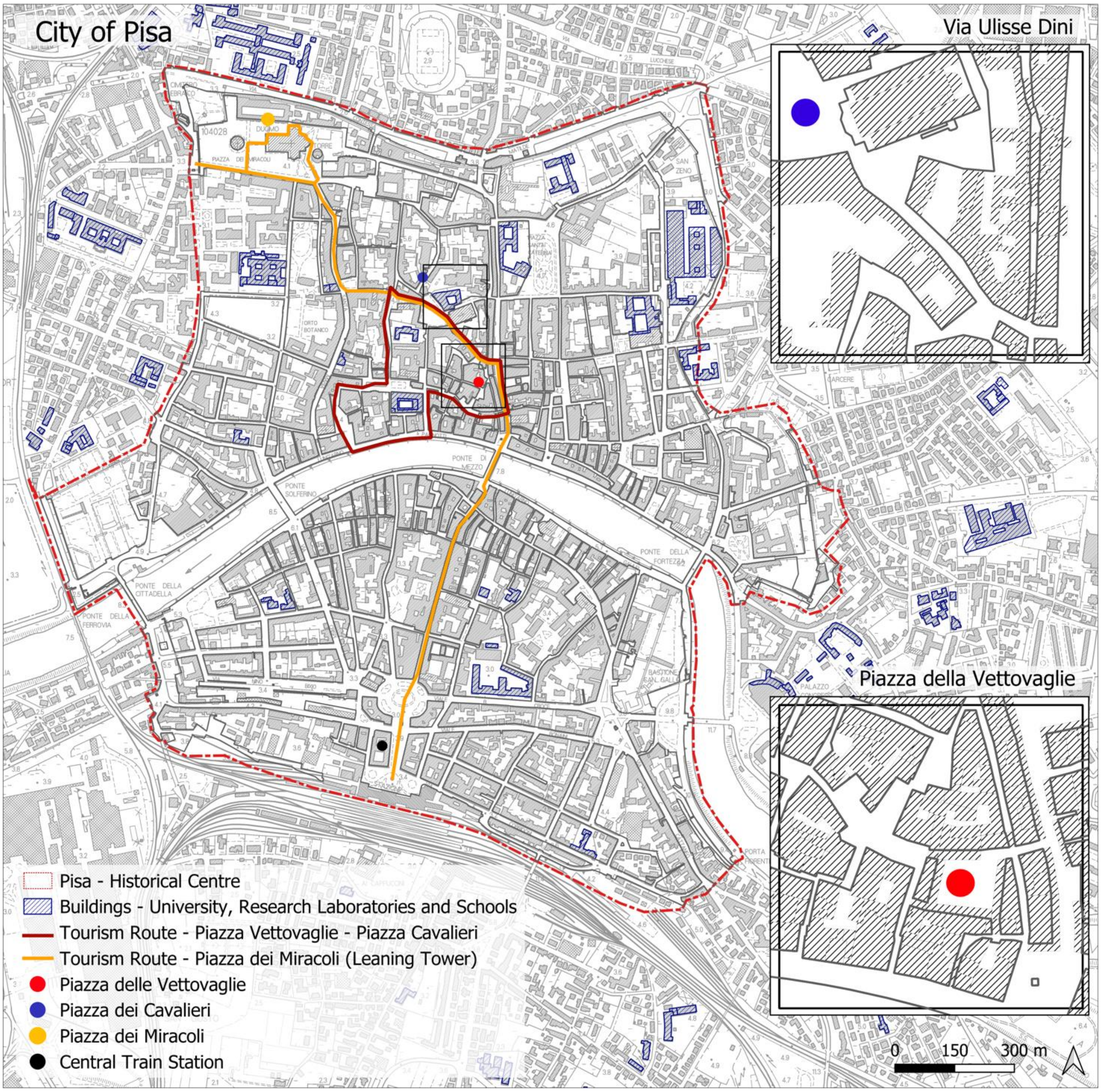

Figure 1. The historical city centre of Pisa, Italy.

3. Dataset

The undertaken work relies on the analysis of the following datasets. Concerning the environment, data from the CTR 2K Geoscopio Toscana (Regione Toscana, 2019) were employed. Apart from the spatial dataset, constructing the ABMs required the identification of existing activities in the areas to capture the changing dynamics. To achieve this, on-site surveying was developed. This allowed the identification of the actual commercial activities (see Table 1) in Piazza delle Vettovaglie, their opening hours during the specified dates – from 6 am on Friday, May 24th 2023, to 6 am on Saturday, May 25th 2023 – and the corresponding public space occupancy at different times of the day. Based on the observed macro-trends, the timeframe was divided into five macro-phases: morning (6-11 am), afternoon (11 am-4 pm), evening (4 pm-9 pm), night (9 pm-2 am), and late night (2 am-6 am).

To develop the Agent-Based Model, data on pedestrian traffic in the area were collected. To achieve this, 10 virtual gates (1-10) within the vicinity were defined (numbered red segments, Fig.2), and pedestrians entering and exiting through each gate were manually counted and registered every timeframe (30 minutes) by reviewing CCTV videos provided by the *Polizia Municipale*. Due to privacy concerns, automated counting of individuals using object detection algorithms was not feasible. However, this manual counting process allowed us to adjust the speed of the videos based on the situation, ensuring an accurate count of individuals.

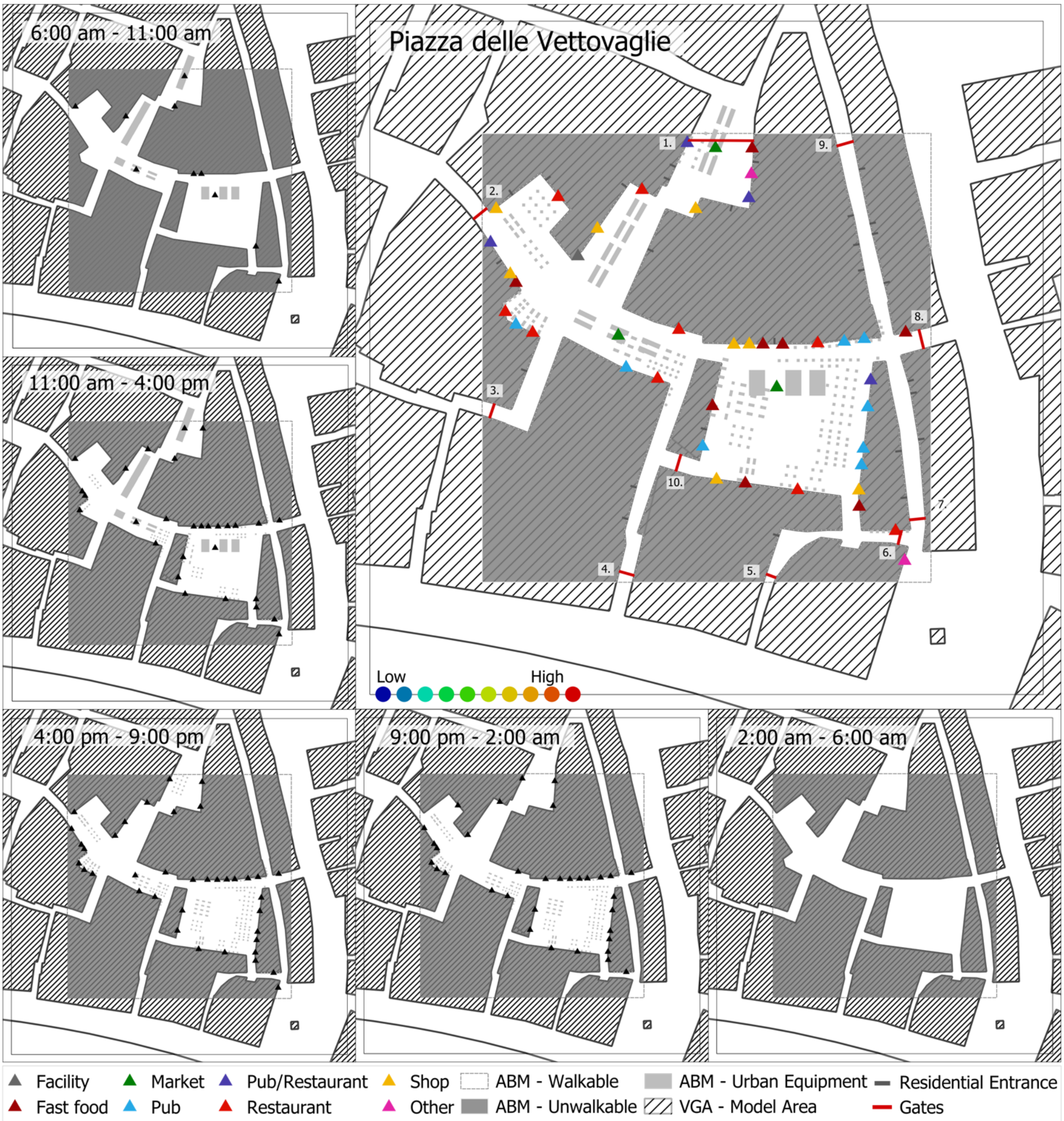

Figure 2. Piazza delle Vettovaglie: virtual gates, commercial activities and urban equipment through time, direct access to buildings.

As regards Via Ulisse Dini, an on-site survey and people counting were conducted from 6 am on Friday, June 21st 2024, to 6 am on Saturday, June 22nd 2024. As previously mentioned, there are no commercial activities in the area. Thus, the resident vehicles parked in the back area of Via Ulisse Dini to the east (Fig. 3) are the only elements that modify the environment and influence pedestrian movement and visibility conditions. In this regard, changes in vehicle disposition over time (Fig.3 and Table 1) and the number of pedestrians entering and exiting through the three access gates (11-13) were recorded: the first to the north, leading to Piazza dei Cavalieri; the second to the south, leading towards Borgo Stretto; and the third to the east, leading to Via Consoli del Mare. Like the first case study – both for a logical comparison of the results and given analogous macrotrends in pedestrian flows and changing in the urban equipment (see Figure S2 in the Supplementary Material) – the timeframe was divided into the same five macro-phases. Note that in both cases the 'gates' are virtual; they are not physical obstacles but rather they represent the points at which pedestrians were counted.

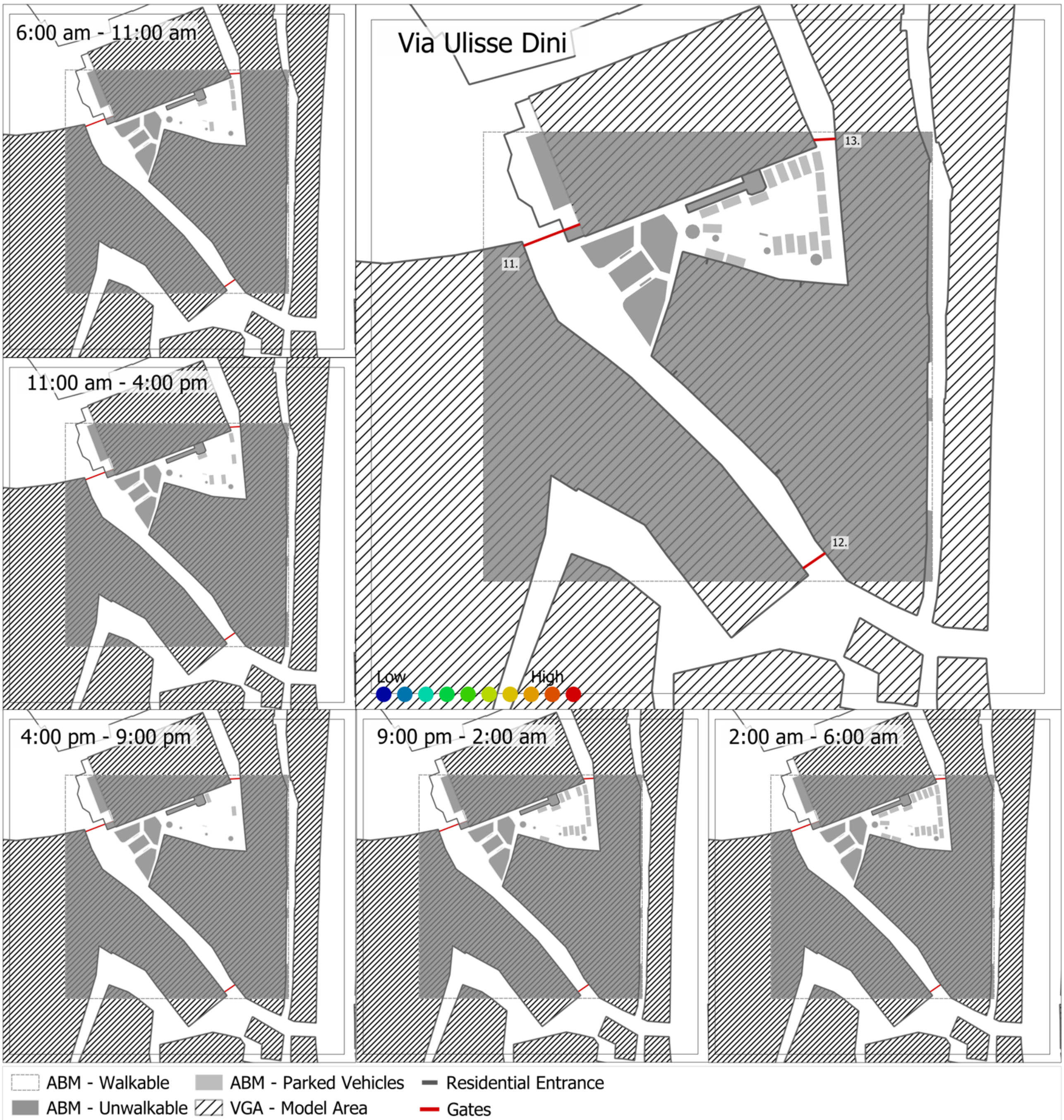

Figure 3. Via Ulisse Dini: virtual gates, urban equipment (vehicles) through time, direct access to buildings.

	CATEGORY	CODE	TIME: 6:00–11:00 Morning	11:00–16:00 Afternoon	16:00–21:00 Evening	21:00–2:00 Night	2:00–6:00 Late Night
PIAZZA DELLE VETTOVAGLIE	Fast Food	F1					
	Fast Food	F2					
	Fast Food	F3					
	Fast Food	F4					
	Fast Food	F5					
	Fast Food	F6					
	Fast Food	F7					
	Fast Food	F8					
	Restaurant	R1					
	Restaurant	R2					
	Restaurant	R3					
	Restaurant	R4					
	Restaurant	R5					
	Restaurant	R6					
	Restaurant	R7					
	Restaurant	R8					
	Restaurant	R9					
	Restaurant	R10					
	Local Market	M1					
	Local Market	M2					
	Local Market	M3					
	Pub/Restaurant	PR1					
	Pub/Restaurant	PR2					
	Pub/Restaurant	PR3					
	Pub/Restaurant	PR4					
	Pub	P1					
	Pub	P2					
	Pub	P3					
	Pub	P4					
	Pub	P5					
	Pub	P6					
	Pub	P7					
	Pub	P8					
	Shop/Store	S1					
	Shop/Store	S2					
	Shop/Store	S3					
	Shop/Store	S4					
	Shop/Store	S5					
	Shop/Store	S6					
	Shop/Store	S7					
	Shop/Store	S8					
	Services	PS1					
	Other	O1					
	Other	O2					
VIA ULISSE DINI	Parking lot	PL1					
	Parking lot	PL2					
	Parking lot	PL3					
	Parking lot	PL4					
	Parking lot	PL5					
	Parking lot	PL6					
	Parking lot	PL7					
	Parking lot	PL8					
	Parking lot	PL9					
	Parking lot	PL10					
	Parking lot	PL11					
	Parking lot	PL12					
	Parking lot	PL13					
	Parking lot	PL14					
	Parking lot	PL15					
	Parking lot	PL16					
	Parking lot	PL17					
	Parking lot	PL18					
	Parking lot	PL19					

Table 1. Commercial activities daily opening hours (above) and vehicle presence (below) through the day.

4. Methodology

The methodology was aimed at developing, for each case study, two models with opposing logics (top-down vs bottom-up) and comparing their ability to intercept risky areas by decomposing crime opportunity based on the dimensions of flows-copresence and visibility-surveillance. This was done in accordance with the rational choice and crime triangle theory and, consequently, following the principles of space-time-movement convergence and crime patterns (see Wortley and Townsley, 2017). Finally, as anticipated, a preliminary attempt to integrate the top-down (SS) and bottom-up (ABM) approaches is proposed. In this section, we provide a detailed presentation of the adopted criminological theory and the methodologies used for top-down modelling through SS techniques and bottom-up modelling through an ABM developed in NetLogo.

4.1 Criminological theory: Routine Activity Theory

As previously noted, the Routine Activity Theory – and crime triangle diagram in particular – serves as an environmental criminology framework aimed at modelling the conditions conducive to crime commitment. According to Cohen and Felson (1979), criminal incidents occur when there is a "convergence in space and time of the three minimal elements of direct-contact predatory violations: (1) motivated offenders; (2) suitable targets; and (3) the absence of capable guardians against a violation" (Cohen and Felson, 1979, 589). These three elements are conceptualized in terms of copresence and visibility, as depicted in fig.3. These dimensions offer an interpretative framework for identifying potential high-risk areas within a specific context. Interpretation is tailored to the crime under analysis. For example, areas with high copresence, such as crowded metros or streets, are more susceptible to pickpocketing, where the offender can act inconspicuously. On the other hand, according to this model, robberies are more likely to occur in sparsely populated and poorly connected areas, minimizing the chance of sudden 'guardian' arrivals and maintaining lower visibility simultaneously. Thus, according to these assumptions, the environment plays a significant role. Both urban configuration and urban design – for example, the relationship between buildings, openings, and streets – affect crime-related environmental conditions (Van Nes and Lopez, 2007), modifying accessibility, intervisibility, and natural surveillance, thus influencing both pedestrian flows and visibility conditions, which directly impact criminal opportunities.

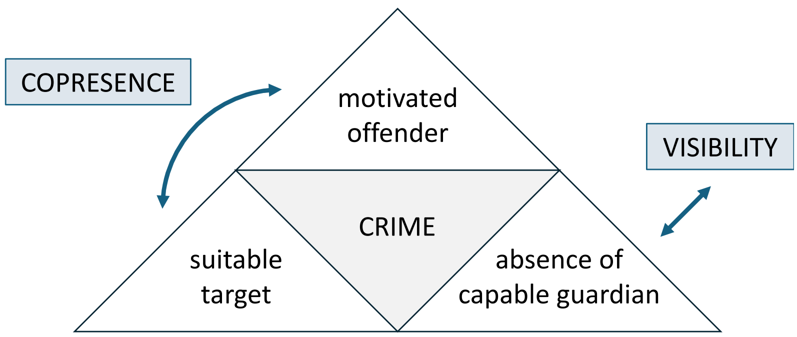

Figure 4. Crime triangle interpretation in terms of copresence-flow and visibility-surveillance measures.

4.2 Space Syntax: Visibility Graph Analysis (VGA) through vision

Space Syntax analysis techniques can be divided into line-based and grid-based. The first – in which Axial Analysis (AA) and Angular Segment Analysis (ASA) are the most used – reduce the space into the system of the fewest-and-longest visual lines able to cover it. Grid-based analysis, namely Visibility Graph Analysis (VGA), decomposes the space into a discrete grid filling the whole space under analysis. The adopted technique for this investigation was VGA. This decision is based on its superior granularity and reliability in estimating pedestrian flows (Turner Doxa Sullivan Penn 2001, Penn Turner 2002, Lopez Baeza et al., 2021), as well as for the extensive set of measures it possesses to describe micro urban environments (Koutsolampros et al., 2019). Particularly, under specific conditions like minimal altitude variation, precise modelling of the environment, and micro-urban scale analysis – effectively comparable to architectural scale – VGA emerges as an optimal technique (Mara et al., 2024). A grid of 0.375m was set for two reasons: firstly, to have a densely packed grid and thus taming the effect of the non-randomised grid highlighted by Dalton et al. (2022). Secondly, to match half the footprint of a human (considered as 0.75m), useful for subsequent integration into the ABM model (see Section 5). The analysed area was 157.5*157.5 sqm to mitigate edge effects, but just 105*105 sqm was considered for the analysis. In terms of measures, after numerous tests on flow estimation, the chosen measure for interpreting copresence – which is probabilistically associated with flows – was through vision. The through vision measure essentially represents the frequency with which a location is crossed over by visual lines generated by the superimposed VGA grid. Turner (2007) demonstrated a strong relation between through vision and human spatial cognition, along with excellent correlation with pedestrian behaviour in both urban (R^2 = 0.62) and building scenarios (R^2 = 0.68). Moreover, VGA through vision exhibited the highest correlation with recorded flows in the very same area (Mara et al., 2024), surpassing also measures coming from other analysis techniques.

As for assessing visibility, controllability was chosen as the measure, capable of identifying less visible areas and providing a metric able to reveal how controllable a location is. Turner (2004) acknowledges controllability as a metric that offers valuable information about the environment from a criminological perspective.

In conclusion, relying exclusively on spatial configuration, we extracted measures of copresence and intervisibility. These measures allowed for the assessment of risky areas based on Spatial Crime Impedance, as defined by Mara and Cutini (2023). This concept, echoing the idea of spatial impedance inherent to space syntax, represents the intrinsic characteristics of urban space in either facilitating or impeding the occurrence of specific types of crimes (Mara et al., 2024a).

4.3 Agent-based Modelling (ABM): Netlogo simulation

Regarding the Agent-Based Modelling (ABM), the platform employed was NetLogo. Leveraging the datasets discussed in the previous Section, the modelling encompassed the following aspects.

4.3.1 Input data utilization

<u>Agents.</u> Pedestrians entering the area through the virtual gates, recorded every 30 minutes, were used as input data. Additionally, the number of pedestrians exiting from each virtual gate was used to probabilistically assign, for each half-hour, the chosen exit for the agents. The agents were further categorised into three groups, according to the dataset (locals, visitors, and tourists).

<u>Environment.</u> The spatial modelling utilised the same base as the top-down model (CTR 2K Geoscopio). The environment was divided into a grid of 280*280 pixels, each equivalent to 0.375 square meters. Commercial activities and their associated urban equipment were included and categorized by type. The temporal component was ensured by the existence of ticks in the model (see below for tick-seconds equivalence).

4.3.2 Agents behaviour

General movement logic. The basic behaviour of each agent involves entering through one gate and exiting through another gate based on the minimum path criterion (Crooks et al., 2015). This approach aligns with the findings of Helbing et al. (2001) and López Baeza et al. (2021), which state that pedestrians move by taking the fastest route and exhibit aversion to changing their chosen path, following the principles of optimization and utility. The agents' movement speed was set with the equivalence of 1 tick = 1/3 seconds, resulting in variable speeds between 1.125 and 1.6 m/s based on the direction they traverse (linear or diagonal), consistent with Henderson's (1971) study where the agents' average speed is 1.34 m/s. Agents can avoid each other and obstacles along their path, making decisions that minimize costs, by assessing the surrounding environment. Like López Baeza et al.'s model (2021), agents make decisions based on the probabilistic choice model.

Specific movement logic. To characterize the model, specific behaviours were defined for each type of agent. Parameters, both visual and behavioural, were set in accordance with Van Nes Yamu (2021, 105. See the Supplementary Material). The percentages of the three types of breeds (tourists-locals-visitors) were determined according to the registered data: morning 13-16-71, afternoon 19-31-50, evening 15-38-47, night 3-85-12, late night 4-24-72 for Piazza delle Vettovaglie, morning 9-13-78, afternoon 27-21-52, evening 19-34-47, night 15-76-9, late night 6-21-73 for Via Ulisse Dini.

Additionally, each type of activity was assigned a certain "attractive power" capable of temporarily changing the plans of the agents in the area, thus simulating the typical behaviour observed in the area. Additionally, based on qualitative observations, a different attractiveness factor for commercial activities has been assigned to each agent: on average, tourists have a 20% likelihood of visiting commercial activities, locals have a 10% chance, while visitors have a 5% chance. Finally, in reference to the first case study, an additional activity was introduced, named 'Vettovaglie-Sant'Omobono nightlife', located in the middle of the squares and active from 9pm to 2am. This qualitative component was added to capture the attraction that the square exerts during the night on pedestrians passing through the area. Indeed, between 9pm and 2am, the square becomes densely populated with people who spend their time there. For the creation of flow and visibility maps, the number of times each pixel was stepped on and observed was recorded for each phase. Subsequently, these data were spatialized and categorized within GIS, using the same colour scale as employed for the SS analysis, to facilitate the comparison.

During the ABM modelling phase, some potential criticisms were identified (see Section 6 and Supplementary Material). It is essential to emphasize that we do not claim this model to be officially validated but rather a plausible representation designed through real data and reasonable assumptions to capture people's movement and visibility differences over time, to discuss their methodological development and overall potential.

4.4 SS and ABM modelling comparison and integration: copresence, visibility, risky areas

Specifically, with both the SS and ABM constructed to extract measures of copresence and visibility, an analysis of risky areas related to street robbery is conducted. Finally, we propose a preliminary attempt of integration of Agent-Based Modelling (ABM) and Space Syntax (SS) by incorporating through vision as a driver for agents moving through the environment, as suggested by Turner (2007). In particular, a new matrix to regulate the general movement logic was calculated, composed of values from the cost surface maps and the through vision metric, first normalized and then weighted. An iterative process was then used to qualitatively assess the effects of this integration on agent behaviour. The tests conducted revealed that the model did not exhibit any anomalous agent behaviours (e.g., inability to reach the destination gate) for through vision values below 12%. This paper proposes then the comparison between through vision (tv) component equal 2% and 10%, to assess both pedestrian flow and visibility (see Section below, last paragraph).

5. Results and Discussion

From the analysis of pedestrian flows entering and exiting the study areas, it emerged that these vary throughout the day and are uneven across gates, highlighting both the different usage of the area along the day and the existence of preferred paths (see Supplementary Material and in particular Figures S1 and S2).

5.1 SS vs ABM: pedestrian flow and copresence

The differences in terms of pedestrian flow estimation are evidently highlighted in fig.5-6. Firstly, note how the configurational nature of flow estimation (SS VGA through vision) is timeless and therefore 'unique' not only throughout the day but overall, depending solely on spatial configuration. Conversely, the ABM presents a different distribution of flows for each interval due to the various variables included in the model. From the ABMs, it is evident how the conditions experienced by pedestrians change significantly through time, both in terms of flow intensity in different moments and patterns.

Regarding Piazza delle Vettovaglie, interestingly 'morning' and 'late night' time frames in the ABM model exhibit more rigid pathways. This is not due to a lower number of pedestrians but rather to the higher presence of visitors compared to locals and tourists, who merely traverse the area. Additionally, the lack of open commercial activities fails to exert any attractive force capable of altering pedestrian routes within the space. Conversely, pathways become more varied during the central hours of the day, with the 'night' time frame standing out due to the co-presence and widespread occupancy of spaces. Furthermore, the southern accesses (gates 3, 4, 5) are essentially deserted during the 'morning' and 'late night' time frames, highlighting potential temporarily isolated areas that may increase low-flow-related crime opportunities and the fear of crime, especially considering the narrow spaces and limited permeability of those areas. These accesses also appear to be weakly traversed according to the SS model. Overall, the east-west traversal axis emerges as the most travelled one during all phases of the day regardless of different commercial activities, functional configurations, types, and amounts of pedestrians and consistently with the SS model, thus reinforcing the configurational logic.

The case study of Via Ulisse Dini reveals more regular dynamics. The predominant flow is from north to south across all time frames, according to the SS model, while the area to the east leading to gate 13 is significantly less frequented, recording a much lower number of pedestrians passing-by (see Figure S2 in the Supplementary material). The ABM model, however, highlights again that the most substantial flows occur during the central hours and shows how the different composition of pedestrians (tourists, locals, visitors) affects movement patterns. Interestingly, the area leading to gate 13 exhibits variations in the paths followed by agents: the different arrangement of cars influences pedestrian routes, encouraging certain paths over others depending on the occupied stalls at different times. Although these variations are not particularly significant in isolation, when considered together with the number of pedestrians passing through the area, the permeability of the area, and the lighting and visibility conditions influenced by the presence or absence of visual barriers, crime opportunities and the fear of crime can experience significant changes despite the simplicity of the case study – which, in contrast to Piazza delle Vettovaglie, has a more regular urban fabric without continuous transitions from open spaces to narrow streets. Overall, the eastern portion of Via Ulisse Dini is much more segregated compared to the main street according to both models. While the SS model suggests that the area might accommodate comparable flows, the ABM more realistically reflects the disparity in flows between the main street and the eastern area, thus proving more effective.

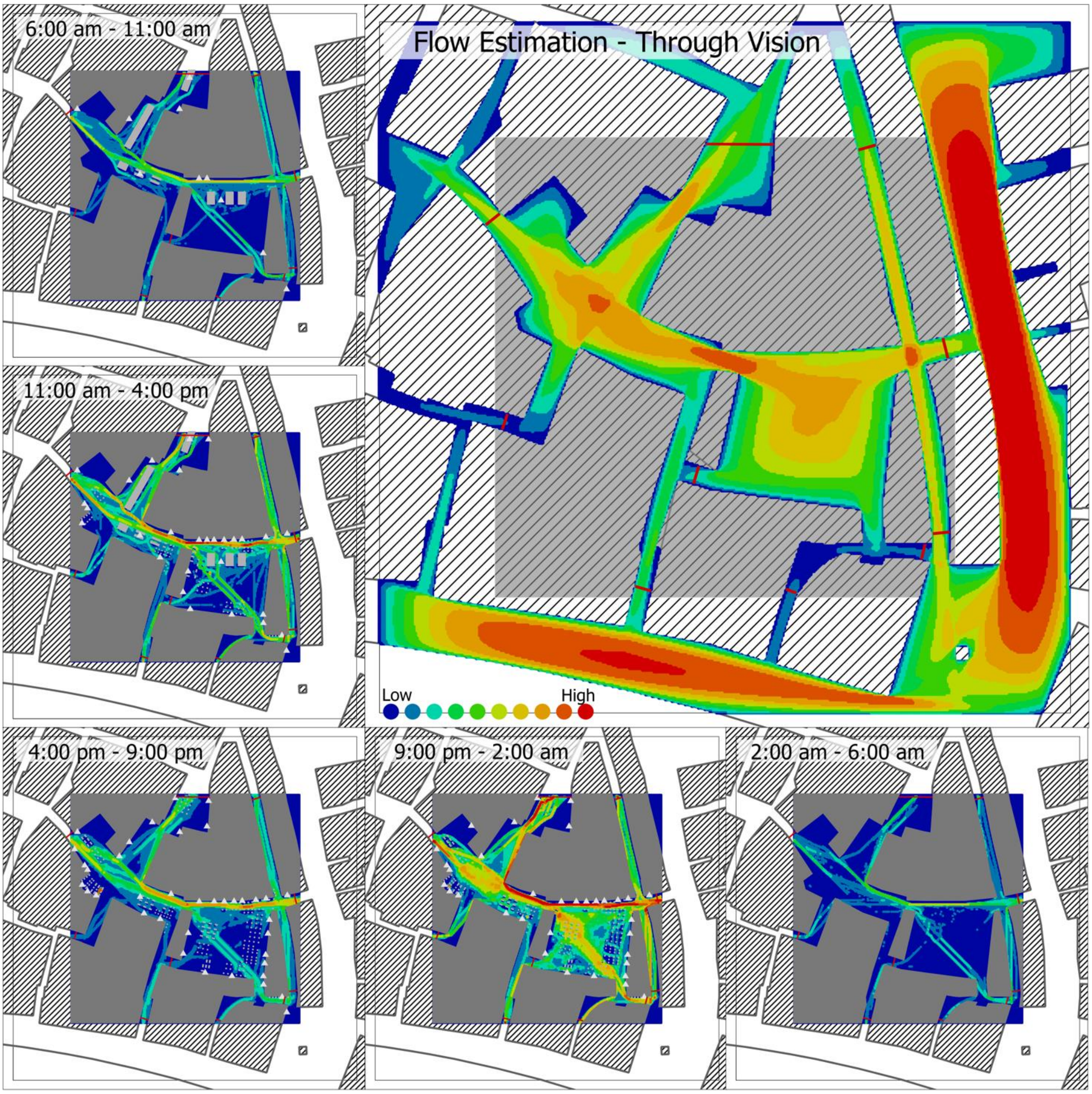

Figure 5. Flow estimation: SS VGA through vision and ABM flows in Piazza delle Vettovaglie.

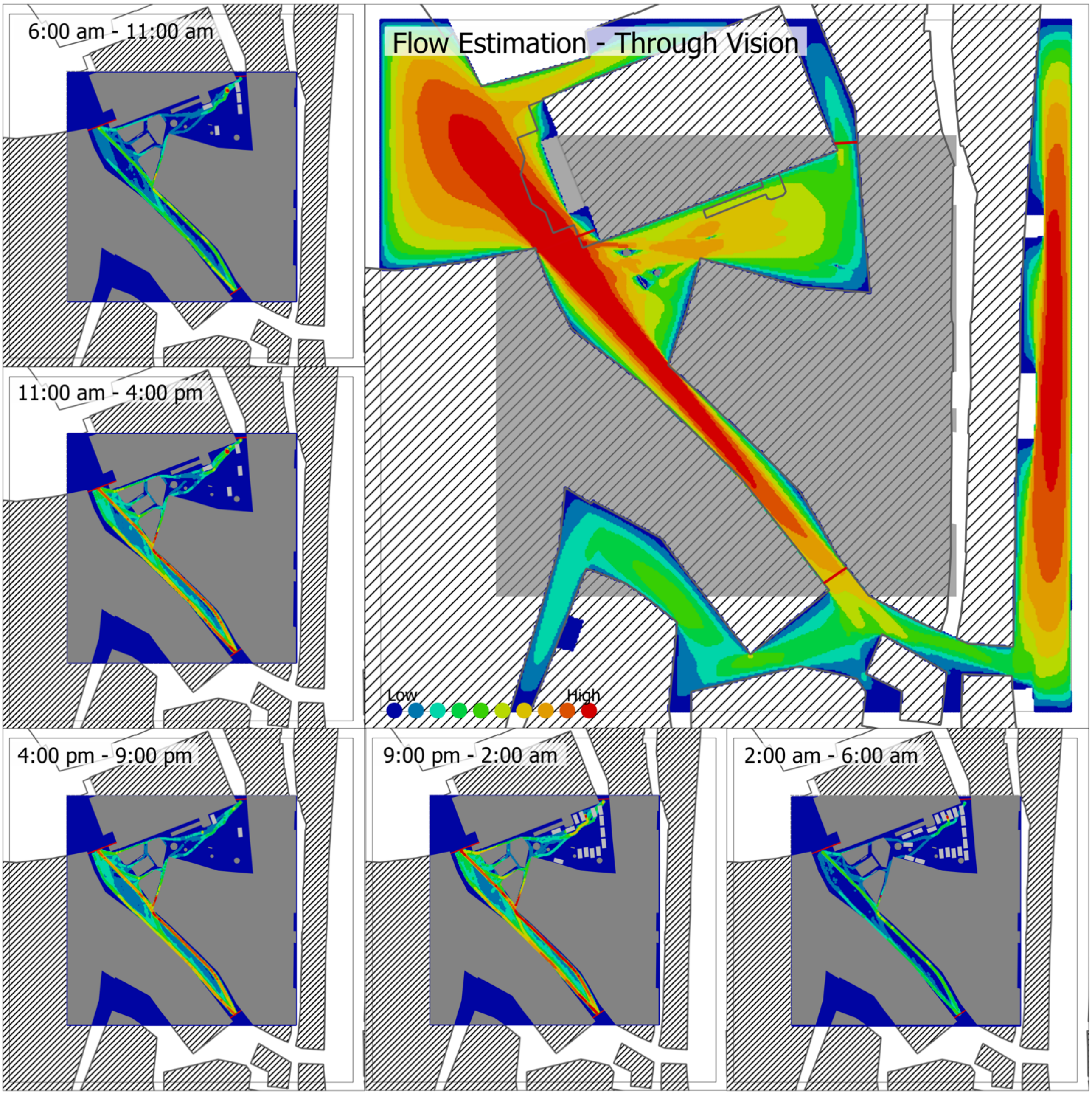

Figure 6. Flow estimation: SS VGA through vision and ABM flows in Via Ulisse Dini.

5.2 SS vs ABM: visibility

Similarly, strong differences between the two approaches emerge in terms of visibility (fig.7-8). In fact, the differences intensify as agents represent an integral part of visibility measurement due to the customizable properties of agents' visual fields. Specifically, with the Agent-Based Model (ABM), there is a 'real' representation of the visual field over time, considering also the obstacles represented by people in the surroundings, thus limiting the visibility of the agents.

Starting from the SS VGA controllability result, the southeast portion of Piazza delle Vettovaglie appears as the more 'controllable' from a configurational perspective. However, a qualitative analysis shows that it is actually less monitored than other portions of the square, at least during certain hours. This is due to the low flows in that portion (eyes on the street), the visual barrier created by people lingering in the centre of the square at 'night', and the poor lighting – both natural and artificial – in that corner, also caused by the presence of the perimeter portico. However, these last variables were not included in either the SS or ABM models. In general, the open spaces gain medium to high values of visual controllability, representing then easily controllable areas, as expected. In contrast, narrow streets in the southern portion and the one running from north to south in the eastern portion are characterized by the lowest controllability values. As said before, the low permeability of these streets (Fig.2) can also significantly impact crime opportunities and the fear of crime. Considering the ABM, visibility conditions change throughout the day, while the most visible areas essentially remain the same. From a qualitative point of view, actual most and less visible areas are better represented by the ABM model. In particular, the diminished visibility in the southeast part of Piazza delle Vettovaglie stands out prominently, presenting a marked contrast with the controllability measure of VGA.

Similar dynamics are observed in the case of Via Ulisse Dini. Both the SS and ABM models are consistent in representing the most controllable areas. However, once again, the ABM more accurately represents the disparity between the eastern and western portions, which actually exhibit very different conditions of natural surveillance due to the significant difference in pedestrian flows. However, a critical issue with the ABM arises: the aggregation of individual agent movements to macro visibility metrics does not allow for understanding whether, in certain short time intervals, large volumes of agents may constitute a significant impediment to overall visibility. In other words, large crowds may form in the short term, reducing visibility and thus generating criminal opportunities (e.g., pickpocketing), but these may be obscured when individual visibility is aggregated to a wide time interval. In fact, the most visible pixels over a five-hour period are highlighted regardless of whether there was an interval during which the area was completely 'obscured' to the view of natural surveillants. To address this gap, a continuous dynamic visualization or reduced temporal interval visualizations could improve outcomes and the highlighting of specific temporal logics, which could be particularly useful for visibility analysis during crowded events, disaster management, or in planning specific crime prevention strategies, e.g., near sensitive spots (bank, ATMs…) or occasions.

In general, the two case studies demonstrate how variations in flows, the composition of pedestrians, open commercial activities, and visual obstacles significantly impact effective visibility, even when these variables are minimized (as in the case of Via Ulisse Dini). Notably, the differing responses of the two models concerning open spaces become apparent. SS models cannot account for effective visibility influenced by the number of people and the temporary obstacles they represent, leading to a representation that is not fully accurate, particularly concerning specific times of the day (those that are less crowded). However, as previously mentioned, further temporal disaggregation could reveal additional significant variations in both flows and visibility in the ABM model.

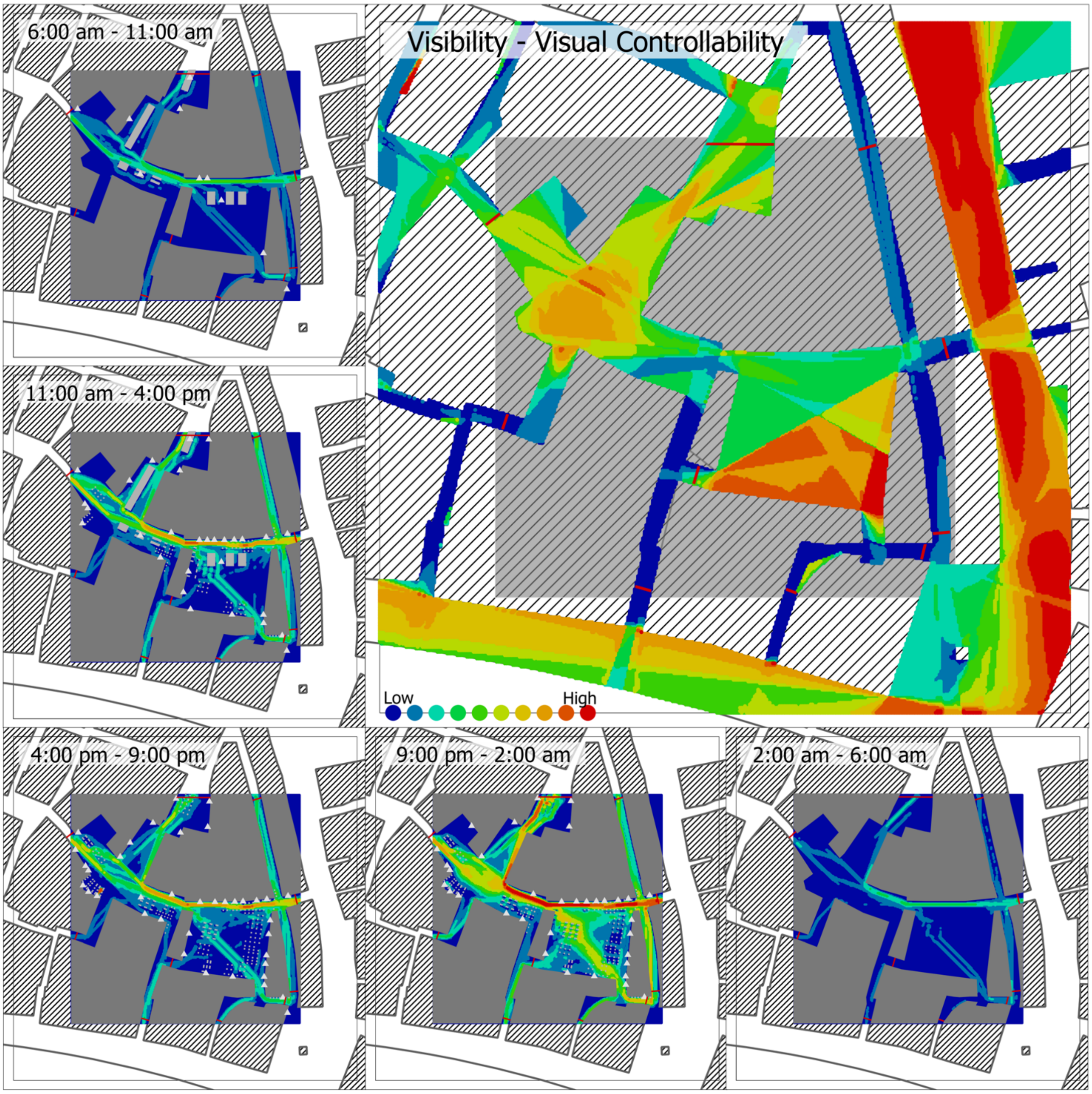

Figure 7. Visibility estimation: SS VGA visual controllability and ABM visibility in Piazza delle Vettovaglie.

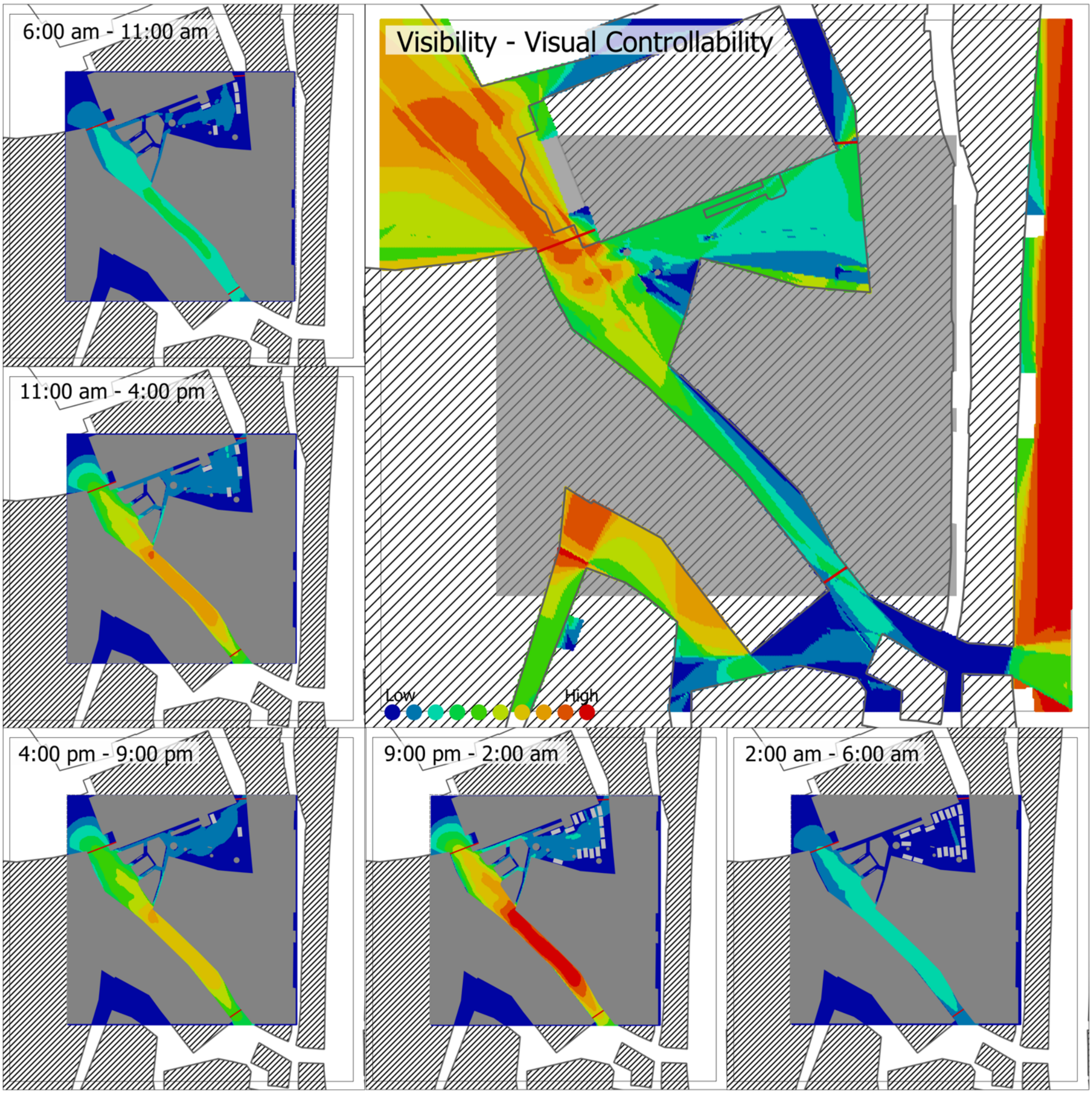

Figure 8. Visibility estimation: SS VGA visual controllability and ABM visibility in Via Ulisse Dini.

5.3 SS vs ABM: risky places

Fig. 9 estimates of the risks of robbery according to the SS and ABM analysis. It shows, for the 'night' timeframe (9 pm – 2 am), areas with the lowest 20% visibility estimated through SS modelling (left) and the lowest 20% walked and viewed pixels from the ABM (right). The night time slot was chosen as, in general, corresponding to the highest risk of robbery (Newton and Felson, 2015). Analysing Piazza delle Vettovaglie, both modelling approaches identify analogous risky areas concerning robbery, albeit with some differences. From the VGA model, the risky places are purely 'configurational': narrow streets or hidden corners. These same risky spots are detected by the ABM, wherein the risky areas are determined in relation to actual pedestrian traffic, highlighting even areas unpredictable by the SS modelling as in the case with the area in Piazza delle Vettovaglie, due to the time-dependent variables affecting the pedestrian behaviour within the square. A different dynamic is observed in the case of Via Ulisse Dini. Here, different areas are highlighted by the two models. The VGA model hardly identifies risky places due to the large spaces that characterize the area, thus making it homogeneously controllable. In this model, only minimal portions of the eastern area are highlighted in purple, the colour that distinguishes risky areas. Completely different is the response provided by the ABM, which highlights the entire open space to the east as a risky area (Fig. 9). This primarily depends on two factors: the very low pedestrian flows that characterize the area throughout the day (see Figure S2 in the Supplementary Material) and the visual obstacle represented by cars rather than pedestrians in this case. This precisely demonstrates how, in general, the logics depicted by the two models are in general similar, but at the same time, it emerges how even for basic cases, the ABM can prove particularly useful in investigations at the micro-spatial and micro-temporal scale.

Therefore, t**he bottom-up model of flow and visibility proves to be crucial from a criminological standpoint**. With ABM, it's possible to identify areas that, for example, due to a high concentration of people, might offer (un)favourable conditions – in the eyes of potential offenders – for committing a robbery, yet providing favourable conditions for other types of crimes, such as pickpocketing, depending on the contingent situation. In these specific scenarios, Piazza delle Vettovaglie is offering high pickpocketing opportunities at night, due to the high pedestrian flows and copresence (see Figure S1 in the Supplementary Material and Fig.5), while in Via Ulisse Dini this risk is persistent during the central timeframes due to the constant high flows in the same direction (see Figure S2 in the Supplementary Material and Fig.6). Actually, both these areas are affected by high drug dealing rate (Mara et al., 2024b). From a criminological standpoint, the mechanisms that lead to pickpocketing and drug-dealing crimes are similar, at least in the early stages, with high pedestrian flows representing potential targets/demand. Again, the low sense of belonging of the inhabitants, the high presence of tourists and the low intervisibility and accessibility between buildings and streets can impact significantly both crime risk and feeling of insecurity (Van Nes and Lopez, 2007; Van Nes, 2021). From this point of view the two case studies, located in the historical centre of Pisa – an historical, touristic, and university city – are quite homogeneous, presenting a series of common elements that negatively impact both real and perceived crime (Mara et al., 2022). In particular, two situations recur in both cases. First, the number of residential buildings, particularly owner-occupied buildings, is low. Most residences are designated for short-to-medium-term rentals to tourists or students, according to the trend of the entire historical city centre. Naturally, these individuals do not establish a strong sense of belonging to the place, nor do they possess the capacity for critical observation of consolidated silent dynamics, making both areas susceptible to neglect by residents and a pronounced sense of fear of crime (Newman, 1972). Moreover, the commercial and touristic nature of the two areas discourages habitation, with some buildings periodically uninhabited. Secondly, related to urban design, the number of direct accesses to residences is very limited, with particular reference to Via Ulisse Dini (Fig. 2-3), leading to an almost total lack of direct control and surveillance of common spaces – except for ground-floor commercial activities in Case of Piazza delle Vettovaglie. This further reinforces the feeling of 'detachment' from perceiving common space as continuous natural extension of private space (Newman, 1972), enhancing the already noted sense of non-belonging to the place. The general obscuring of the public area generated by the portico concerning the Vettovaglie area and, in general, by the narrow streets and the lack of balconies and a limited number of window openings, do not facilitate natural surveillance phenomena and have an impact on street safety (Van Nes and Lopez, 2007). Given the general homogeneity of the area from this point of view, these aspects have been considered qualitatively. However, considering their relevance to the concept of crime opportunity, they will be subject to further modelling investigations in the future, in an attempt to include the complexity of the urban form, the constitutedness of the streets, and the concept of potential targets to further facilitate comparison between different case studies through the definition of risk indices.

In general, the aforementioned aspects that the two selected study areas share might seem limiting, reducing the utility of the modelling performed or the observations that can be drawn from it. However, particularly concerning the Italian case, these same contextual conditions are often found in university historical centres, so the observations made can be transferred to similar contexts, and the adopted modelling techniques can be immediately replicated in other similar case studies.

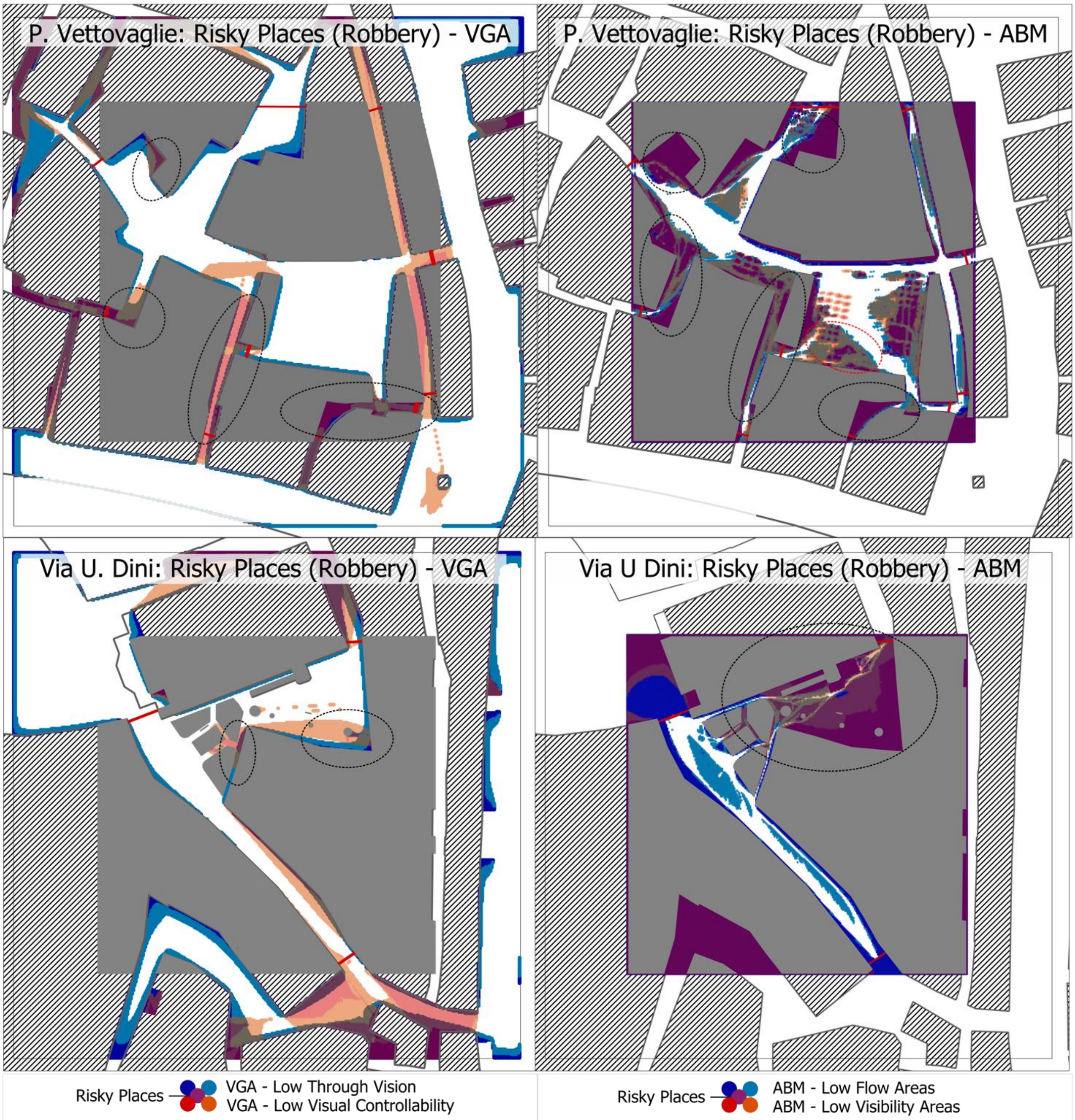

Figure 9. Robbery risky places: SS 20% lower through vision values combined with SS 20% lower visual controllability values (left) and ABM 20% lower flows and visibility values (right) for both case studies.

5.4 ABM and SS: preliminary proposal for a joint application

This integration could potentially allow, at least in theory, the integration of the capabilities of both tools. Fig. 9 illustrates the different distribution of flows and visibility fields in three distinct scenarios: the first without through vision integration, the second with 2% component of through vision, and the third with 10% through vision component. Observing the results, the distribution of flows after integration is less rigid, and there is greater flexibility in the paths taken by agents. According to Space Syntax theories, this component could hypothetically enhance the predictive capabilities of the model, given the ability of SS in estimating pedestrian behaviour (see Section 1). However, at present, this hypothesis stands as a preliminary conjecture requiring thorough exploration, rigorous testing, and extensive discussion to be further explored taking into account also hybrid models developed to assess the role of configuration in pedestrian movement (thread started by Turner and Penn in 2002), crowd movements (Kim and Kim, 2023; Riu et al., 2024) or adaptations from emergency simulation models (Pont et al., 2023). Nevertheless, the proposition persists that the amalgamation of a bottom-up approach, implemented through ABM – adept at incorporating the temporal dimension and characterizing the model with data-driven environmental variables – alongside top-down configurational matrix variables such as SS – proficient in predicting pedestrian movement and wayfinding logic with remarkable precision – constitutes a captivating and promising avenue for assessing pedestrian flow and visibility at both the urban and micro-urban scales.

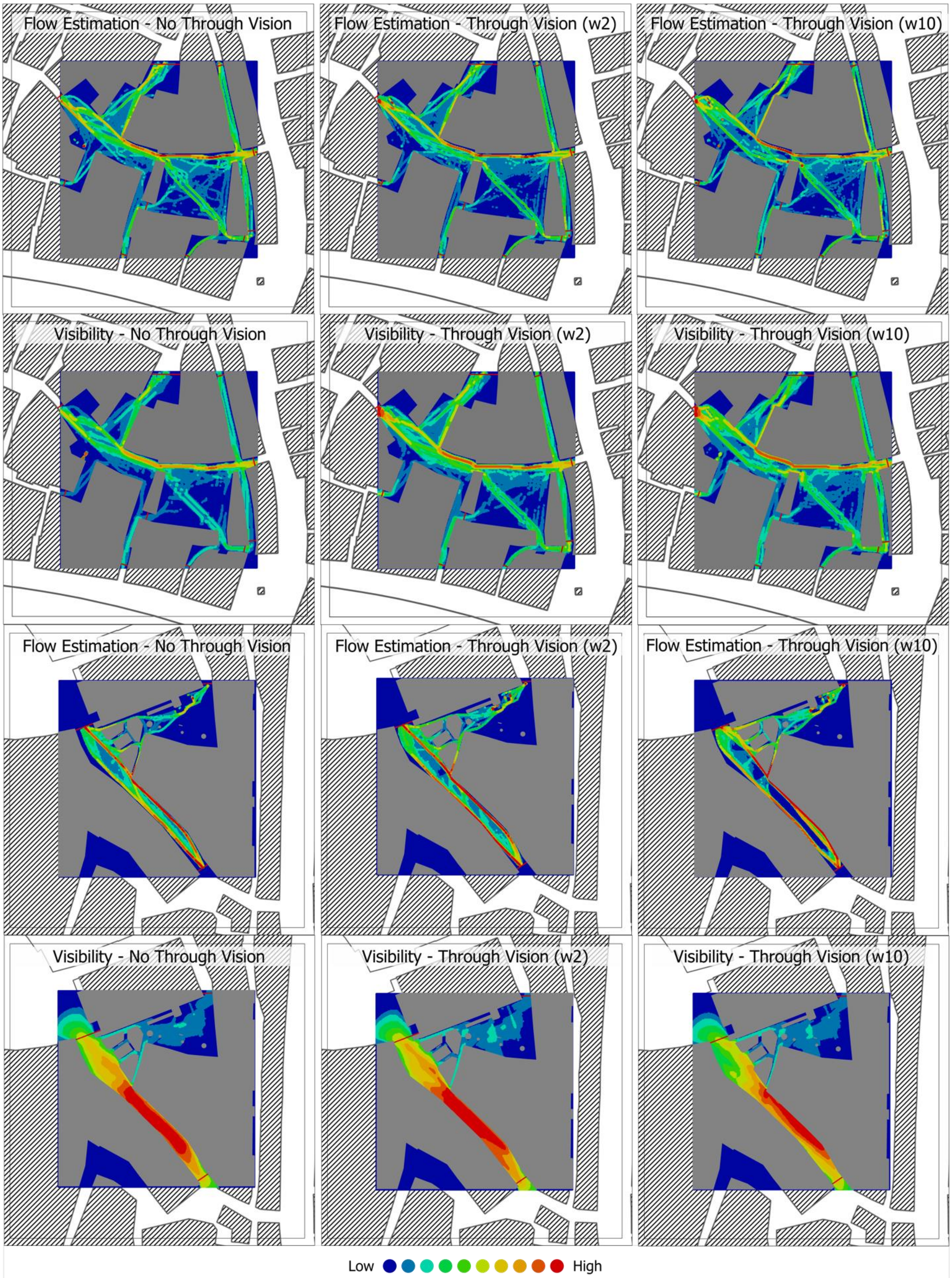

Figure 10. SS and ABM combination for the night time slot. Comparison between ABM flow and visibility estimation without through vision component (left) and agents guided by SS VGA through vision component: flow and visibility estimation map [tv = 2%] (centre) and flow and visibility estimation map [tv = 10%] (right) for both Piazza delle Vettovaglie (above) and Via Ulisse Dini (below).

6. Conclusions

The study compared the differences between top-down and bottom-up approaches – specifically, Space Syntax and Agent-based Modelling – in interpreting pedestrian movement, visibility, and ultimately in defining risky areas through the construction of an interpretative framework of environmental criminology. From the comparison, it emerged that Space Syntax is better for estimating general flows but lacks in addressing temporal issues. ABM can be as detailed as desired, but demands a substantial amount of data, behavioural assumptions, and time in construction. However, ABM is undoubtedly superior in responding to very specific needs due to its high degree of customization and the ability to include the temporal component, which is crucial in the field of crime prevention and, in general, in exploring in detail social dynamics at the microscale.

As anticipated, even from the simple case studies conducted – considering a rather basic interpretative framework – substantial differences in estimating pedestrian flow, visibility and, consequently, potential risky areas emerged. However, the case studies were not thoroughly investigated in this paper. Indeed, the main purpose of this study was to frame the problem, propose the devised methodological approach, and push it to the extremes to showcase the critical aspects and potentials, thus stimulating further debate on the role of models in modelling pedestrian movement and visibility in the context of urban security and crime prevention. Finally, an embryonic attempt at integration between the SS and ABM approaches was proposed. Throughout the work, numerous insights and challenges emerged. The main considerations derived from these are outlined below:

- The ABM included numerous variables, all justified from a methodological perspective through reference to other relevant studies or the integration of qualitative aspects. However, it is now necessary to operate with more rigour and thoroughly analyse both qualitatively and quantitatively the effect of each of these variables on the model, refining it and avoiding unnecessary or scarcely justifiable elements. Moreover, also human spatial behaviour should be further investigated to understand how the 'attractive power' of places change over time (Esposito et al., 2020; Yan and Kalay, 2005). Furthermore, the potential usefulness of additional input data that would further orient the model must be evaluated, especially for validation purposes.
- The complexity of the ABM did not correspond to a similar complexity regarding the underlying interpretative criminological framework. Therefore, it is necessary to compare alternative models, also concerning the supporting environmental criminological theories, and consider the rigorous integration of any other elements useful for defining crime potentials, such as number of targets, permeability, constitutedness of the streets, dwelling types, lighting, and their impact on fear of crime also (see Van Nes et al., 2016).
- Quantitative comparisons between the results should be conducted to appreciate the differences and, consequently, attempt to define both functional visualisations and 'dangerous' threshold values for each type of crime. For example, ABM could potentially allow for identifying intervals where copresence is conducive to increasing or reducing the risk of specific crimes, such as defining threshold below which the risk of experiencing certain crimes increases (e.g., robbery), or thresholds above which the risk of experiencing other types of crimes rises (e.g., pickpocketing). Additionally, investigating the impact of the specific environment on these thresholds, as well as their impact on the fear of crime represents an intriguing aspect.
- The aforementioned quantitative analyses should ultimately be oriented towards the development of a rigorous methodology and precise guidelines aimed at creating a decision support crime prevention model, adaptable to different situations and easily replicable in various contexts. This would provide objective tools to address the

issue of security and disaster management in cities, with a view to promote sustainable and liveable environments.

7. Data Availability Statement

The data supporting the findings of this study are available upon request from the corresponding author, FM. The data are not publicly available due to restrictions imposed by the entity that granted the acquisition of such data under the signing of a specific agreement.

8. Author Contributions

Conceptualization, F.M. and V.C.; methodology, F.M. and V.C.; software, F.M. and D.A; validation, F.M., formal analysis, F.M. and D.A.; investigation, F.M. and D.A.; resources, V.C. and N.M.; data curation, F.M. and D.A.; writing—original draft preparation, F.M.; writing—review and editing, F.M, N.M. and V.C.; visualization, F.M. and D.A.; supervision, V.C.; project administration, F.M. All authors have read and agreed to the published version of the manuscript.

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Supplementary material

Environmental criminology background

Within the strands identified by Wortley and Townsley (2017), studies on the behavioural dynamics of potential offenders have emerged through the lens of the rational choice perspective (Cornish and Clarke, 1985) and situational dynamics that can either incentivize or disincentivize criminal actions (Clarke, 1976; Wilson and Kelling, 1982). The analysis of these dynamics leads to the formulation of crime scripts (Cornish, 1994), which are frameworks delineating a series of rational choices culminating in a particular criminal act, accompanied by specified preventive measures. Furthermore, the examination of crime patterns encompasses the convergence of space, time, and movement, as well as the concepts of crime generators and attractors (Felson, 1979; Eck, 1995; Brantingham and Brantingham, 1995). In conjunction with these interpretative models, targeted strategies have evolved over time through interventions and policies. Notable instances include physical modifications to the built environment advocated by Newman and subsequently endorsed by the first Crime Prevention Through Environmental Design (CPTED). Then, interventions aimed to foster social cooperation and a sense of community belonging (2nd CPTED, see Cozens and Love, 2015), as well as those focused on enhancing sustainability and liveability (Mihinjac and Saville, 2018), with crime being an essential component to obtain that. Furthermore, multi-layered analysis and potential interventions involve investigating the impact of specific environmental characteristics on individuals and crime (Van Nes et al., 2016).

Agent-Based Model additional information

NetLogo was selected due to its user-friendly language and compatibility with Geographic Information Systems (GIS). Initially, Open Street Map (OSM) was used for extracting the commercial activities in the area. However, due to discrepancies of the Piazza delle Vettovaglie case study compared to the current situation and our aspiration for a highly detailed simulation model, an on-site survey was conducted. Additionally, by reviewing CCTV footage, additional information was extracted, including the opening times of commercial activities, spatial occupancy of urban equipment, and identification and counting of different 'types' of passers-by: locals, visitors, and tourists (see Section 4.3). The survey identified 44 activities in Piazza delle Vettovaglie, categorized into 8 groups: pubs (P1-P8), restaurants (R1-R9), pub/restaurants (PR1-PR4), local markets (M1-M3), fast food outlets (F1-F8), shops/stores (S1-S8), services (PS1), and others (O1-O2). The case study of Via Ulisse Dini presented instead 19 parking lots (PL1-PL19).
Regarding the general movement logic of the agents, to minimize the influence of cognitive models on agent movement patterns, as stated by Jiang and Jia (2011), a complex cognitive model was avoided. Instead, a cost-surface map, calculated from each origin gate to all other gates, was used. Agents were set so that once a decision is made (probabilistic choice model, see López and Baeza, 2021), they cannot change their minds until completing the previous action.
As for the specific movement logic, the breeds follow the scheme presented by Van Nes and Yamu (2021). Tourists have a sight field angle of 30° and move one cell before making a new decision among pixels in their field of view. Locals, with a sight field of 15°, move three cells before deciding on the destination among nearby pixels. Visitors, referred to as average persons by Van Nes and Yamu (2021), have a sight field of 7° and move five cells before making a new decision.

Potential improvements to this model include input data that could add complexity to the model – if deemed necessary, while taking into consideration the KISS rule – or could be used for model validation. Specifically, data regarding the correspondence between entrance and exit gates for each pedestrian could be used, to avoid the probabilistic assignment of the origin-destination path. Additionally, a gradient indicating areas more frequently traversed by pedestrians over time could be useful, as shown by Crooks et al. (2015). Finally, data input about the varying attractiveness of each function or commercial activity on passers-by could provide insights for further development. The dataset of actual crimes committed, if sufficiently granular in terms of spatiotemporal location, could also represent an opportunity for model validation.

Registered flow in the area

The pedestrian flows entering and exiting both the study areas exhibit variation throughout the day and are uneven across gates, as illustrated in Supp Fig 1-2. For what concerns Piazza delle Vettovaglie, particularly noteworthy is the peak presence in the area during night-time hours, between 11 pm and 2 am (Supp Fig 1a). Moreover, there is a discernible disparity between the number of pedestrians entering and exiting during this timeframe (compare Supp Fig 1b-c), indicating prolonged copresence rather than mere passage of individuals. In addition to the aforementioned peak, a general trend emerges in the increase of people populating the area during the intervals of 11 am - 3 pm and 6 pm – 9 pm. Examination of each gate individually also unveils significant disparities in the volume of pedestrians passing through, thereby creating diverse scenarios (environmental conditions) concerning copresence and natural surveillance (eyes on the street) for those traversing it. These conditions, based on the assumptions posited (rational choice + crime triangle), impact both the risk of crime and the perception of insecurity.

Via Ulisse Dini, characterized by a simpler spatial layout and only three virtual gates, exhibits an average pedestrian flow comparable to that of Vettovaglie, excluding the outlier of Friday night (compare Supp Fig 2-1). The pedestrian flow pattern over time is represented by a triple curve indicating peak periods at 11 am – 2 pm, 6 – 9 pm, and 11 pm – 2 am, similar to the flows registered in the medium-crossed gates of Vettovaglie. Two additional key characteristics emerge: first, a significant difference in people counting between gates 11-12 and gate 13, clearly indicating a preferential pathway (Supp Fig 2b-c). Second, a nearly perfect match in pedestrian flows going-in and going-out from gates 11 and 12 over time, emphasizing the preferential north-south axis (which is along one of the main tourist route, see Fig. 1), few residential buildings, and lack of activities that 'retain' passers-by in the analysed area – which would otherwise create a shift between the two curves, as observed between people going-in and going-out in Vettovaglie. As for Piazza delle Vettovaglie, also Via Ulisse Dini is characterized by substantial night-time flows due to student nightlife on Friday nights.

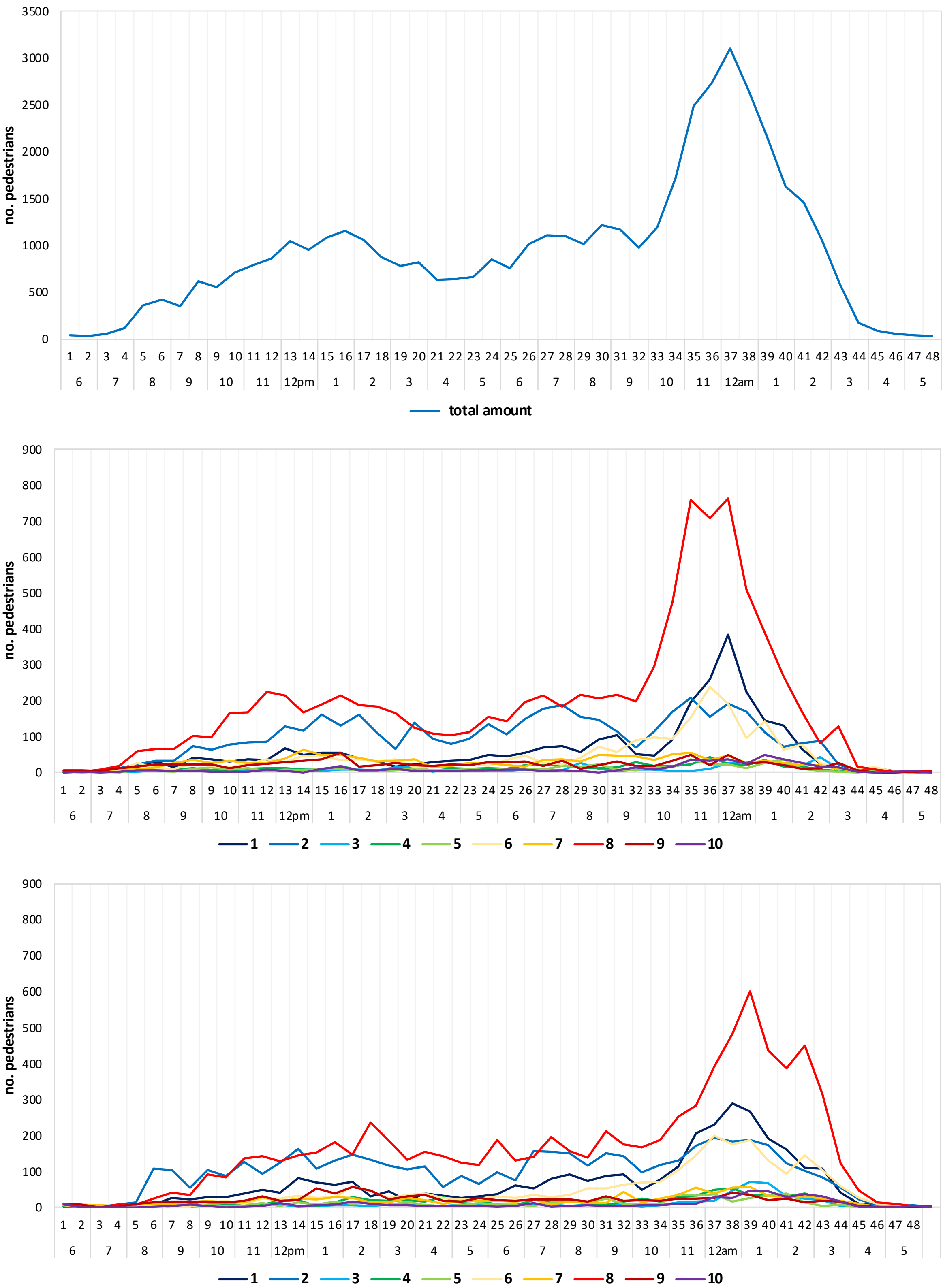

Figure S1. Total amount of pedestrian going-in and going-out from Piazza delle Vettovaglie for each timeframe (a). Amount of pedestrian going-in (b) and going-out (c) per gate for each timeframe.

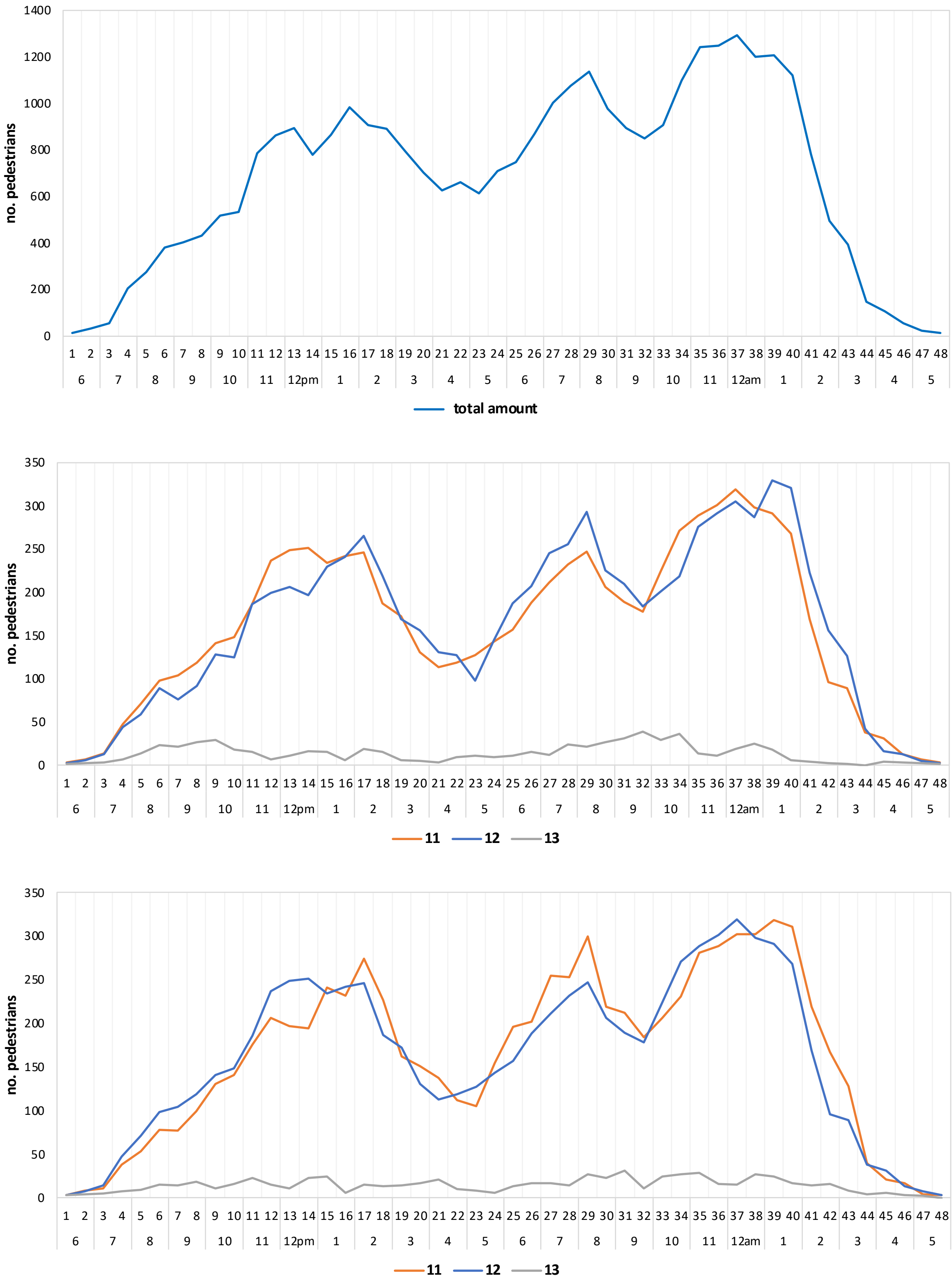

Figure S2. Total amount of pedestrian going-in and going-out from Via Ulisse Dini for each timeframe (a). Amount of pedestrian going-in (b) and going-out (c) per gate for each timeframe.

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