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Behavioural-based risk of the Built Environment: Key Performance Indicators for Sudden-Onset Disaster in urban open spaces

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ABSTRACT

The assessment of risk in the Built Environment (BE) involves understanding the inseparable relationship between the physical space and its users. In emergency management, particularly during Sudden-Onset Disasters (SUODs), effective evacuation is crucial for individuals' resilience in BE. Key Performance Indicators (KPIs) offer a quantitative approach to risk assessment, facilitating a systematic evaluation of various risks within BE. The research focuses on seismic events and terrorist acts as relevant SUODs and proposes KPIs derived from literature-based indicators to assess the impact of construction and morphological features of Built Environment Typologies (BETs) and user-related factors on urban open space risk (behaviors, exposure, vulnerability). These KPIs are then applied to established BETs, that are archetypes from real-world configurations of urban open spaces, and tested through seismic and terrorist risk scenarios along with emergency simulations. Results indicate significant variations among BETs, emphasizing the importance of factors, such as geometry (static KPIs) and evacuation behaviour (dynamic KPIs) in determining risk levels. Evacuation route length and complexity emerge as critical in larger BETs, while insufficient safe areas pose challenges in smaller ones. This KPI-based approach is recognized as a crucial step toward establishing a comprehensive metric for risk assessment in BE open spaces, with potential real-world applications to quantify the efficacy of risk mitigation measures. The results demonstrate the KPIs' potential in quantifying disaster risks and user behaviours, representing a crucial step towards an overarching metric for BE-risk assessment during SUODs in open spaces.

List of main abbreviations and symbols

BE	Built Environment
SUODs	SUdden Onset Disasters
SLODs	SLow Onset Disasters
KPIs	Key Performance Indicators
BET	Built Environment Typology
OS	Open Space

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SB	Baseline scenario for SUODs, see Fig. 5
SE1, SE2	Intermediate and collapse seismic risk scenarios, see Fig. 5
ST1, ST2	Terrorist acts risk scenarios with moderate (i.e. armed assault with cold weapon), see Fig. 6 and significant dynamic (i.e. motor vehicle running on the crowd) effects, see Fig. 7
BId	Balance index of debris
$R_{RC,tot}$	Road resistor coefficient
V_{loss}	Pedestrian speed conservation
O_i	Obstacle friction rate
SOS	Temporary Secure Open spaces
E	Exposure index
TN_{95}	Normalized evacuation time (95th percentile of evacuees)
PN	Crowd effects
FN_{95}	Mean flow rate at the exit
R_{evac}	Number of Evacuees for SUOD from surrounding buildings in the OSs
CR	Number of deaths/casualties
O_p	Obstacle protection rate

1. Introduction

About 3.8 million km^2 and 790 million people in the world are relatively highly exposed to hazards, and climate change is likely to further increase multiple risks, affecting the magnitude, frequency, and spatial distribution of hazardous and disastrous events [1–3]. Assessing the safety of the Built Environment (BE) means considering the inseparable relationship between the physical space and its users [4]. These considerations are integral throughout the Disaster Life Cycle, typically comprising four main phases: Mitigation, Preparedness, Response, and Recovery [5,6]. This model helps frame issues related to disaster preparedness as well as recovery after the event, as communities are continuously engaged in at least one phase of the cycle.

Among these phases, immediate response and evacuation activities following a disaster are crucial for user resilience in hazard-prone built environments, especially for Sudden-Onset Disasters (SUOD), which can rapidly alter environmental conditions. In such circumstances, users should generally try to reach a "safe zone" or condition in the shortest amount of time, if possible. The boundary conditions are compounded in Open Spaces (OS), where dimensions, use and crowding conditions, over time and space, can be more significantly complex and critical than indoor environments, often lacking clear evacuation indications [7,8].

Among these aspects, the fundamental ones to be evaluated certainly include the conditions of OS users' behaviour, response and movement in the disaster-affected BE, as well as the connection between these user-related issues and the threats identification, the morphological and constructive characteristics of evacuation paths towards the OS (e.g. as in the case of earthquakes, in which OS are attractors for evacuees due to their dimension) and from the OS (e.g. as in the case of terrorist acts that can happen in a certain OS or a specific part of it), and, finally, the evaluation of the best mitigation strategies, including those related to emergency procedures and evacuation paths [8–13]. Nevertheless, to support the management of such a process, it is necessary to define adequate risk indicators (Section 1.1) and perform tests through the application to significant scenarios (Section 1.2).

1.1. The potential of use KPIs for risk assessment in the BE

The assessment of disaster risk, resilience and users safety in OSs requires quantitative metrics, capable of evaluating the effectiveness of different mitigation strategies in specific scenarios. The development of these metrics goes through the definition of Key Performance Indicators (KPIs) [14,15], which provide data-driven insights to optimize resilience, safety, and sustainability, fostering informed decision-making for stakeholders and policymakers alike.

Each disaster has unique characteristics, and user behaviour in dealing with the risk varies depending on the origin and specific effects of the hazard on the built environment [16,17]. Focusing attention only on SUODs, the assessment approach significantly differs between natural disasters (e.g., earthquake) or man-made ones (e.g., terrorist acts), leading to substantial distinctions in the users' behaviours and the specific risks inducing casualties [13,16,17]. Consequently, defining metrics capable of considering both single and multi-risk approaches presents an operational challenge in determining appropriate KPIs [15].

Furthermore, each BE, and thus each OS, can be characterized by specific features concerning the considered single and multi-risk, mainly given the interactions of hazards with the BE morphology, construction issues, physical vulnerability, users' exposure and social/individual vulnerability. Data from past events and simulations are widely used to derive KPIs, which provide insights into the current scenario conditions and guided decisions for retrofitting and enhancing resilience, tailored then to specific cases.

Therefore, it is worth noting that the methodology for defining the KPIs is strictly linked to their intended purposes and the performance to be measured [14,15,18]. Thus, in the reference field, they should comprise the human-BE interactions and dependencies in emergency conditions. Moreover, KPIs are generally classified into leading and lagging KPI. Leading KPI measures activities that significantly impact future performances, while lagging indicator measures the output of past events [19]. The processing methods of KPIs are a subject of debate in the scientific literature, with several studies addressing the topic [15,20–22], However, a significant gap exists in the absence of a multi-risk approach and the limited inclusion of behaviour-based phenomena in emergency and evacuation assessments [8].

1.2. Built Environment characterization for developing and testing KPIs

Most of the previous works on the development, testing, and application of risk indicators focus on the development, testing and application of risk indicators focus on analysing and finding immediate and customized responses for specific catastrophic events that have occurred in OSs (e.g. earthquakes, tsunami) in specific locations or case studies [23–25]. Although these studies can be founded on reliable scenarios, especially in the case of the analysis of real-world disasters, limitations due to case-specific conditions and analysis can affect the development and testing of KPIs, leading to poorly generalizable results.

To overcome such issues, previous research moved towards the definition of archetypes of BEs starting from the collection of typological features of real-world BEs and provided application to various contexts on BE performances, including risk assessment based on simulation models (e.g., seismic, floods, climate-related) [26–30]. Concerning the use of such archetypes, it is worth noting that related data can be generated with precision and control, ensuring high reliability and theoretical predictive power, since archetypes allow controlled experimentation and exploration of potential solutions [30–32]. Thus, the definition and application of KPI-based assessment on typological models and scenarios pursue a sort of parametric assessment of recurring factors while maintains adherence with real-world scenarios on which they are based [31]. Regarding the combination with simulation tools, the focus often remains on post-event response measures, especially while providing applications to urban scenarios, although models of immediate emergency analysis have been consolidated, playing a crucial role in forecasting and optimizing evacuation strategies [33–35]. In this sense, KPIs can then be included in proactive risk assessment approaches [20,36,37], which involve predicting potential hazards based on the specific characteristics of the BE and the behaviours of the exposed users involved.

In particular, previous works provided archetypes of OSs prone to several risks, by defining, as an output, the Built Environment Typologies (BETs) [31]. BETs have been set out by analysing a sample of 1111 squares in Italian cities prone both to SUODs and Slow Onset Disasters (SLODs), selected for their representativeness in terms of morphological and use features [12,38]. At the same time, the focus was on historical contexts due to the relevance of their vulnerability features as well as to the potential for experiencing multi-risk scenarios, i.e. multi-SUODs [39]. In particular, the analysed sample consists of squares which typically attract visitors and tourists, due to sights, monuments and heritage, thus increasing the exposure in terms of the quantity of users present in the scenario before a SUOD. In this sense, they also act as typical attractors for terrorist acts, being ideal soft targets [40,41]. Moreover, considering the physical vulnerability of the historical buildings facing the square, the BETs are susceptible to potential high damage in case of earthquakes, due to the building collapse and the generation of debris outdoors [4]. For each square, data on morphological, geometric, functional, and constructive aspects that influence SUODs, were collected from GIS databases. A cluster analysis was performed based on these data to identify the BETs describing multi-risk scenarios, by selecting five characterizing parameters (morphology, height of fronts, number of accesses, slope of the ground, and presence of green areas). Using the k-means algorithm, the cluster analysis identified five distinct groups of OSs with specific dimensional and functional characteristics. Combining cluster analysis outcomes with an evaluation of supplementary variables (i.e. presence of special buildings and ratio between the height of the built fronts and the width of the OS), nine final BETs were identified.

These BETs are aimed to facilitate a comparative assessment of OS features influence on overall risk and represent the base for simulation-based methodologies that can include analyses of disaster-affected scenarios, considering the safety and behaviours of users under such conditions [35], as the ones analysed in this paper. This typology-based approach for preliminary and quick assessment purposes is common in various methodologies, such as those related to structural [27,42], comfort [43] and energy analyses [26]. Although approximations in setting up the scenarios and providing performance simulations outputs, this approach enables a preliminary analysis based on essential parameters for BE description that can be also managed by the KPIs, as discussed in Section 1.1.

1.3. Work aims

The aim of this paper is hence to define a set of KPIs, for SUOD risk assessment in the immediate evacuation of OSs, by developing and applying them in the context of BETs.

KPIs are selected from the analysis of existing literature-based indicators, modified and integrated according to a behavioural-based perspective [8]. Each KPI can assess the main consequences of specific interactions between the users, the BE and the hazard effects in emergency and evacuation scenarios. At the same time, KPIs can be applied to more than one SUOD, if similarities exist in emergency phenomena and user effects from a behavioural perspective. Furthermore, KPIs can be calculated using outputs from validated simulation models.

The investigated SUODs concern terrorist acts and seismic risks, since they involve opposite dynamics in the evacuation process [44–46]. Indeed, terrorist acts may necessitate evacuating the OS to move away from perpetrators and associated risks, while seismic events typically attract users to the OS due to its larger dimensions in respect to the surrounding streets, allowing for distance from buildings and debris. Nevertheless, no spatiotemporal overlapping of these SUODs is considered in this work, to mainly focus on assessing each KPI's ability to describe unique issues associated with each specific risk scenario [47].

The application context of the BETs refers to archetypes of squares in Italian historic city centres [31,39,48], as discussed in Section 1.2. Nevertheless, this work methodology aims to design KPIs to ensure their application also in real-world scenarios. BETs serve as a basis for a preliminary assessment of the main KPI-based risk levels depending on the considered SUODs and typological square features. Therefore, the proposed KPI-based assessment could be further refined and adapted to specific case studies, allowing for comparison of risk impact due to tailored features compared to those of typological (BET) models [15,27,31].

The present work also contributes to the project "BE S^{2}ECURe - (make) Built Environment Safer in Slow and Emergency Conditions through behavioural assessed/designed Resilient solutions", funded by the MIUR (the Italian Ministry of Education, University, and Research). BE S^{2}ECURe pursues the development of holistic and behavioural-based methods, tools and guidelines for the risk assessment and mitigation in the OSs. In this general framework, previous BE S²ECURe steps provided the definition of the BETs investigated in this work [30,31], as well as developed and validated simulation tools utilized in this research [35].

2. Materials and methods

The methodology is structured into two main cores, following the scheme outlined in Fig. 1. Section 2.1 describes the process of defining the final KPIs, selecting by applying the SMART (specific, measurable, assignable, realistic and time related) approach [19,49] to literature-based Performance Indicators (PIs) selected from seismic risk [8,50] and to terrorist acts risk literature [51]. Section 2.2 presents the application of KPI calculation in BET scenarios, elaborated to represent different archetypes of OSs, with the aim of demonstrating their capacity to jointly analyse individuals-environment interactions across different risk scenarios.

2.1. Definition of KPIs for SUOD risks

The KPI selection is focused on the leading type and is based on the analysis of PIs selected through specific literature reviews conducted in previous phases of the BE S²ECURe project [50,51]. Specifically, these works identified 34 PIs aimed at describing seismic and terrorist acts risk and measure BE features and users' activities, all of which significantly influence future performance in risk prevention contexts and align with the overall research project objectives [30,52].

The subsequent subsections outline the steps of the KPI selection method: 1) explanation of the *SMART approach*, enabling the selection of KPIs through a series of functional and synthetic indicators; 2) definition of KPI types based on the simulation behavioural-based approach, categorizing them as static or dynamic.

2.1.1. SMART approach

Among the numerous approaches to define KPI, some standards regarding KPI have been developed, with specific referred to industrial processes. The International Organization for Standardization outlined various standards, such as ISO 22400 [53] for manufacturing operations management, ISO 14031 [54] for environmental performance evaluation and ISO 13053 [55] for defining Six Sigma performance improvement methodology. However, due to their focus on industrial processes, these approaches are complex to apply to issues of risk in the BE. Instead, the approach elaborated by Doran can be consider one of the most suitable for application on multi-risk investigation of BE [49]. Doran proposed the SMART philosophy to formulate the management goals and objectives, considering them critical steps in company's management process. This philosophy exhibits parallels with the disaster management process, wherein the aim of measurement pertains to the performance of the BE instead of a company. The SMART represents:

- **Specific**: Targeting a specific area for development;
- **Measurable**: Quantifying/indicator for risk improvement;
- **Assignable**: Designating responsible personnel/team;
- **Realistic**: Establishing achievable objectives with available resources;
- **Time related**: Setting a timeframe for achieving results.

To tailor the SMART philosophy to behavioural-based simulation of BE, it has been elaborated and adapted as follow:

- **Specific**: Targeting a specific risk or risk-combination for BE;
- **Measurable**: Quantifying/indicator for risk;
- **Assignable**: Assigning to one or more risk-prone element of the BE;
- **Realistic**: Establishing objectives related to behavioural issues or involving in specific actions;
- **Time related**: Aligned with specific investigation periods for SUODs, linked to evacuation times.

To be finally elected as a KPI, each PI are precisely evaluated according to SMART principles, and only those meeting all five requirements are selected. Subsequently, the KPIs are selected to be valid for seismic risk, terrorist acts risk or both. The combination is not contingent to a temporal or spatial overlapping of the risks in the BE (e.g. as coupled events), but rather on an approach to SUOD, acknowledging the possibility of terrorist acts and earthquake occurring at different times has been taken into consideration [47].

2.1.2. Type of KPIs: static and dynamic

The indicators were screened from the scientific literature related to the studies about BE risks. The indicators were firstly categorized accordingly to specific physical or behavioural aspect [4,37,39,50,51,56].

The preliminary analysis of the collected PIs led to a distinction between static and dynamic KPIs. Static KPIs can be directly

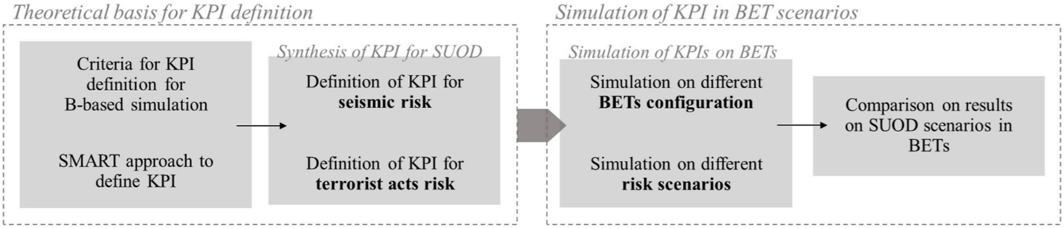


Fig. 1. Representation of the methodology workflow for definition and testing of KPI.

calculated through the application of an equation and consider the geometric and morphological aspects of the BE (under normal and emergency conditions) that influence users' behaviours, choices, and habits. In this regard, the main aspects to consider when choosing a static KPI include:

– The presence of permanent obstacles, which are part of the BE consistently (street furniture, dehors, traffic bollards etc.) or temporary, as in the case of debris generated by SUODs such as earthquakes, which affect the evacuation process;
– Crowd density, representing the number of people in the area regardless of their location and distribution in space.

Conversely, dynamic KPIs consist of indicators whose calculation and interpretation require human behaviour simulations. In this research, these simulations have been executed within the archetypal BETs [57,58], by using an agent-based evacuation simulation model, previously developed and tested [35]. This model employs experimental-based rules to replicate the behavior of each OS user during a terrorist act or earthquake, as well as the mutual interactions among the users, the BE and the specific SUOD effect [35]. The model is based on a common simulation logics and flowchart, but it is then implemented with specific rules to represent the evacuation process activated due to a terrorist act (users leaving the OS) or to an earthquake (users gathering within the OS). The spatial contexts for agent-based simulations are the archetypal BETs to account for typological OS characteristics: geometric layout, uses, damage levels [59]. An overview of the simulation model is provided in Appendix A.

The main simulation outputs (i.e., evacuation time, physical contact among users, number of casualties, evacuation flows and paths for SUODs) can provide the basis for the development and application of KPIs. Due to the stochastic behavioural factors introduced in the model, at least 10 repetitions of each scenario have been provided to evaluate statistical values from the main simulation outputs. Indeed, the authors would like to remark that any other validated evacuation simulation model could be used to derive basic data on

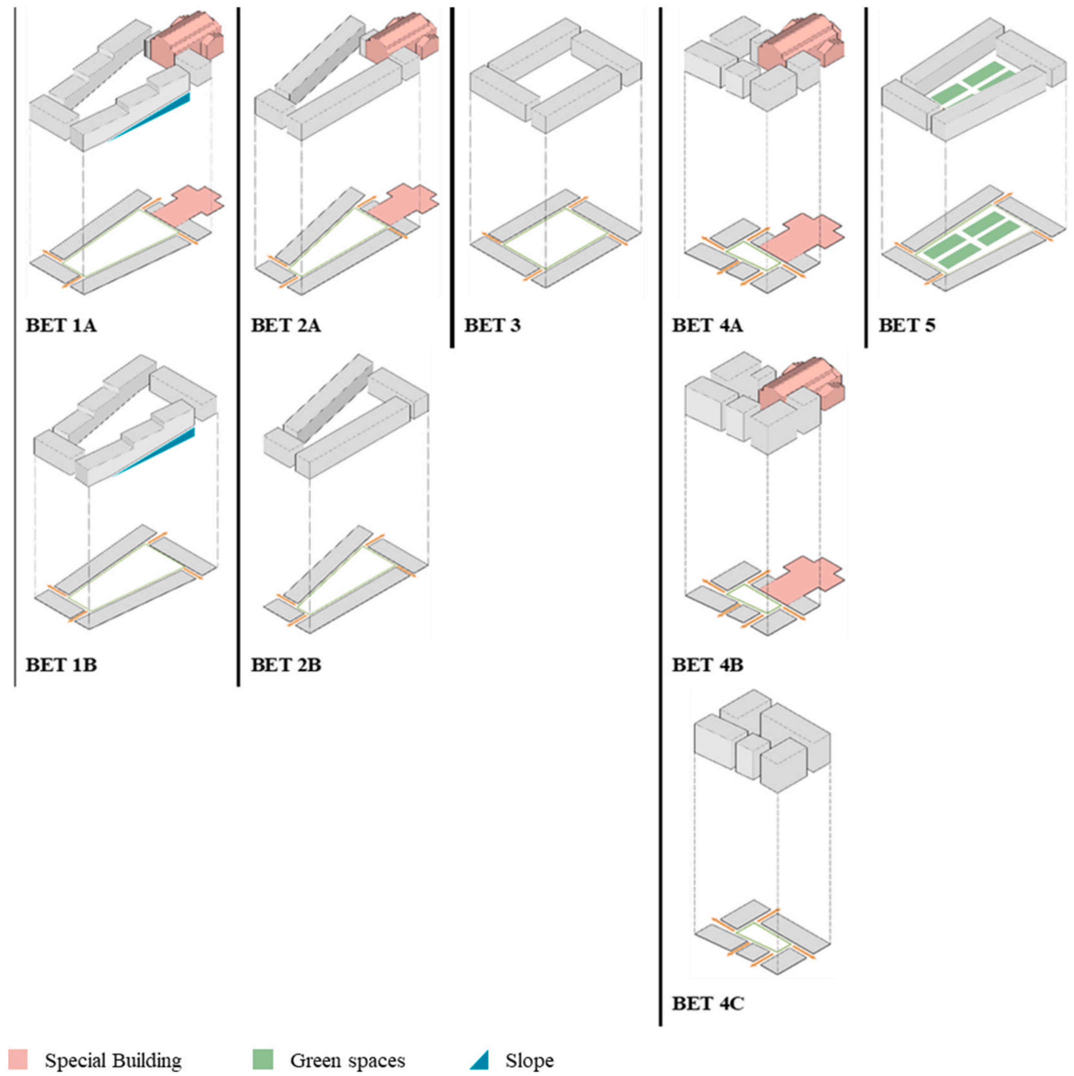


Fig. 2. Outline summary of the BETs elaborated by the authors from BESECURE project [31].

users' behaviours, employing similar logics of the proposed KPIs to digest simulation output and produce the required result.

The considered outputs to describe the human-centric SUOD risks in the BE primarily focus on [29,59,60]:

- Evacuation times;
- Crowd interactions, related to the density of people, contacts that may also lead to falls and thus increased risk. The number of users for each type of area (e.g., safe areas for SUODs) and their position in space, including concerning critical conditions (e.g., overcrowding, interactions with debris, and so on), are critical in simulations (as opposed to static KPIs), as they encompass individuals' trajectories from a general perspective (e.g., countering the use of each patch in the BE by users, along with the associated times);
- Behavioural issues, the primary objective of the simulation, the set of behaviours adopted by users who are involved in specific actions, including their location (e.g., the number of people falling during the simulation time and their location).

2.2. KPIs application in BETs scenarios

The validity of the selected KPIs, has been tested through the application to the BETs in Fig. 2 [31], which have been assessed susceptible to both SUOD risks, as discussed in Section 1.2. First, BETs are characterized to distinguish different recurring scenarios in terms of morphology and dimensions. In this sense, it is worth noting that BET 1A and 1B have a slight slope of about 10% on the long side (see blue triangle in Fig. 2), which affects the evacuation speed. Furthermore, BET 5 is the only one that has a fenced green space in the centre, which limits the safe free space available to users in the event of an earthquake, making the evacuation paths in general the most complex, as it is not possible to cross the square diagonally. Moreover, some BETs are also characterized by the presence of a Special Building (pink building and plan area in Fig. 2), such as a church, a museum, a theatre or another typology of building open to public and potentially involved in crowding conditions. The Special Building mainly assumes a relevant role in risk assessment due to its function in respect of the users' presence, since scenarios assume that it can attract many users, such as visitors, and thus contribute to the increase of crowding. In particular, the BET model considers that the visitors of the special building, where present, are placed outdoors, in front of the building, such as while waiting to enter it, so as to maximize the crowding conditions of the square [35] (compare with modelling issues in Appendix A).

Each of the nine identified BET has been analysed through the elaboration of 3 different configurations of the space in terms of street furniture, handcrafts and other obstacles placed in the square, as most representative of cases related to historical OSs [35]: C1 - bollards with chains; C2 - a monument; C3 - both bollards with chains and a monument. As a relevant example, Fig. 3 resumes these configurations within the BET 1A [61]. The only exception in the configurations is BET 5 (Fig. 4) that has only two configurations: the base one, only with the flower beds (C1) and the one with a monument (C2).

In the application to the BETs, risk conditions have been reliably modelled according to the analyses conducted on earthquakes and terrorist acts in previous phases of the BE S^{2}ECURe project.

The seismic risk of the BE has been estimated referring to the Italian territory (highly seismic) [4]. During an earthquake, evacuees tend to gather in the centre of the square, away from possible collapse of buildings elements. The evacuation process comprises a flow of people into the square, arriving from the surrounding buildings and adjacent streets, in addition to those already in the square. Based on these data, two increasing risk scenarios to be analysed are defined, considering the overturning of the built fronts according to the rapid assessment methods [4]: SB - base scenario without debris; SE1 - earthquake scenario with two built fronts and two access streets affected by damage and debris presence in the OS; SE2 - earthquake scenario with all the built fronts and access streets affected by damage and debris presence in the OS. The related scenarios are graphically represented in Fig. 5 for the BET 1A example.

Concerning terrorist acts, two types of attacks have been defined [32]: an armed assault, when a man threats a crowd with a sword or a knife (ST1); a vehicle attack, when a person bursts into the BET driving a vehicle to crash a target (in this case, the church or the dehor for BET without Special Building), running over the users placed along its trajectory (ST2). The base scenario (SB) represents the starting condition without a specific risk, being thus analogous to the base scenario for earthquake. Figs. 6 and 7 respectively show the ST1 and ST2 terrorist acts risk scenarios for each geometric configuration, with reference to the example of BET 1A, by mainly showing

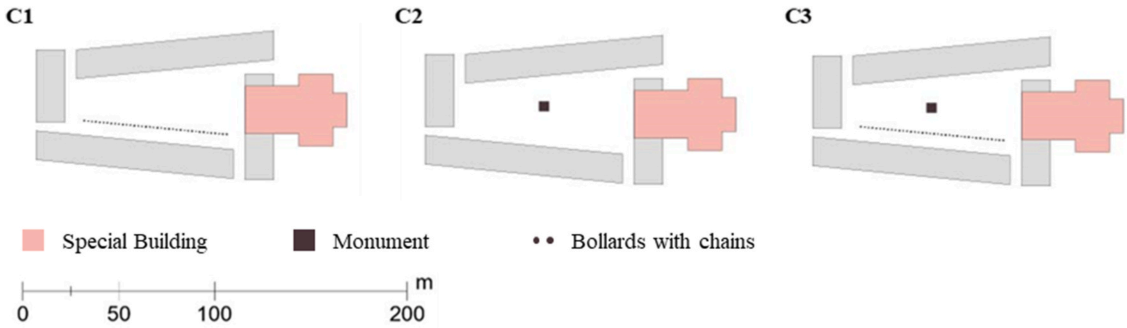


Fig. 3. Example configurations of BET1A: C1 - with the presence of bollards with chains, C2 - with the presence of a monument, C3 – with the presence of both bollards with chains and a monument. The elements characterizing these three configurations are used also in BET 1B, BET 2, BET 3 and BET 4.

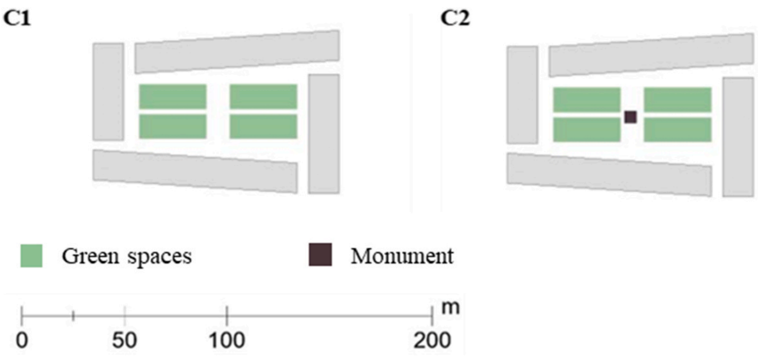


Fig. 4. Configurations of BET5: C1 - base, C2 - with the presence of a monument.

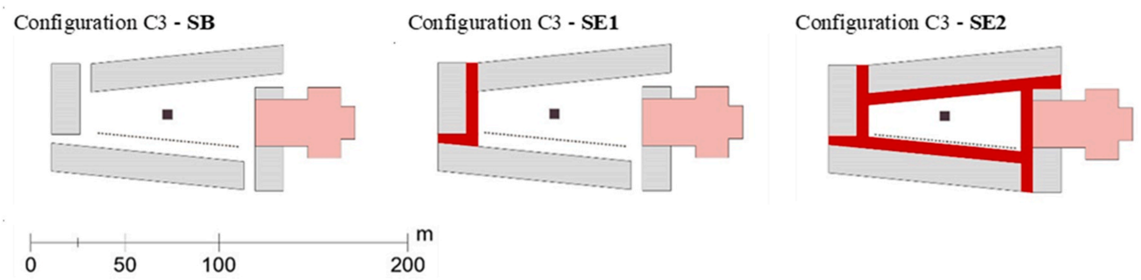


Fig. 5. Synthetic schemes of debris area for earthquake scenarios in configuration C3. In the configuration C1 and C2, the debris scenario is the same. Similar situation occurs for the other BETs.

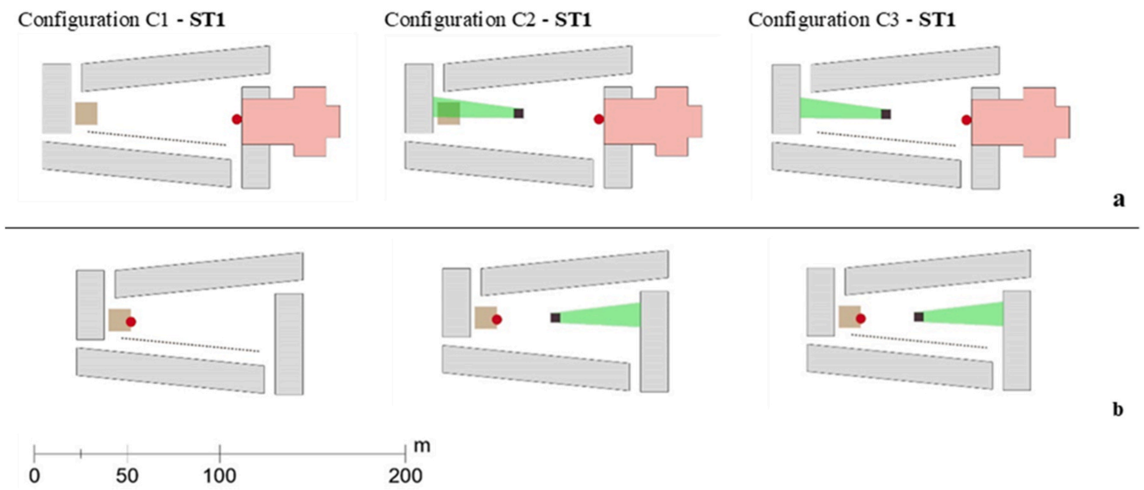


Fig. 6. Example of representation of the attack points (red dot) of the ST1 scenario in the BET 1A with (a) and without (b) the Special Building. In the three geometric configurations, the point of attack does not change but the safe area of the BET does (green area), due to the protection provided by the obstacles depending on the position of the attacker relative to them. Similar situation occurs for the other BETs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the position of the point of attack. Indeed, the furniture position and dimension contribute to limit the attacker' sight with respect of the point of attack, determining a different safe area which edges derived from the conjunction of the attacker's position with the boundaries of obstacles and/or building frontiers [62]. The boundary of these safe areas is calculated by considering a straight line starting from the attacker's position. When the Special Building is present, the point of attack is referred to the area in front of it. In fact, the Special Building represents a typical soft-target for terrorist acts, since it attracts users and thus an attack organized nearby can increase the potential damage on the users themselves. Moreover, the Special Building can also have a symbolic value in view of its intended use, thus increasing the attack effects and the desirability for the potential attackers [41]. Therefore, considering the

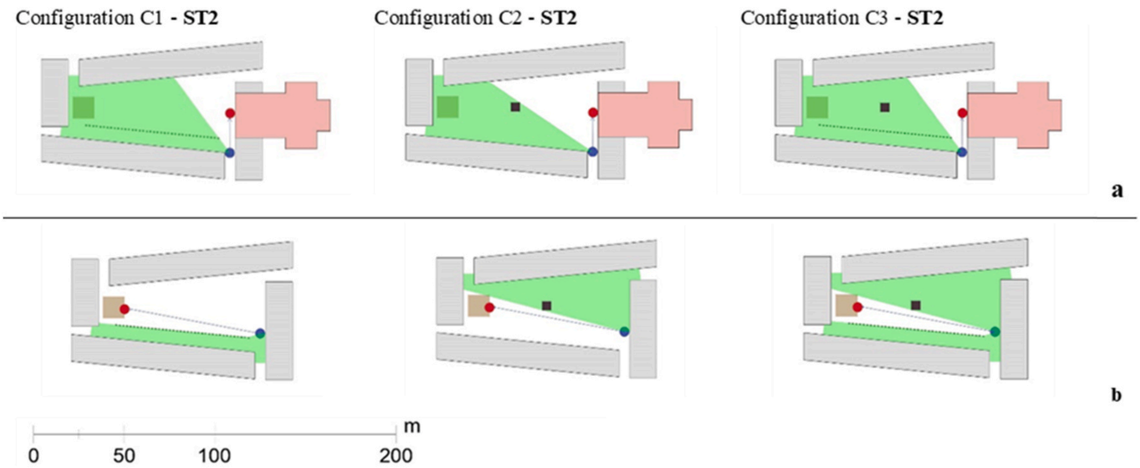


Fig. 7. Example of representation of attack trajectories (blue to red dot) of the ST2 scenario in the BET1A with (a) and without (b) the Special Building. In the three geometric configurations, the trajectory does not change but the safe area of the BET does (green area), due to the protection provided by the obstacles depending on the position of the attacker relative to them. Similar situation occurs for the other BETs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

evacuation process, crowd dynamics also depend on the interactions between the dense crowd placed in front of the Special Building, and the attackers [31]. Instead, when the Special Building is not present in the BET, the most crowded area is the one of the dehors (e.g. open-air terraces of bars and restaurants), and thus the point of attack is herein identified according to its higher desirability for crowding level. It is worth noting that the overall crowding is more relevant in the BETs with a Special Building, and thus also the users-attackers interactions in evacuation can mainly affect these scenarios [31]. Figs. 6 and 7 also point out the effects of the position and dimension of street furniture and other obstacles on ST1 and ST2, respectively. Street furniture and other obstacles in the square contribute to limit the attacker' sight with respect of the point of attack, determining a different safe area which edges derived from the conjunction of the attacker's position with the boundaries of obstacles and/or building frontiers [62]. The boundary of these safe areas are calculated by considering a straight line starting from the attacker's position. Nevertheless, regardless of the typology and point of attack, as well as of the BET configuration, users will always tend to move away quickly from the attackers, directing the entire evacuation process far from them towards the BET safe areas and access streets.

According to the definition of the KPIs type given in Section 2.1.2, in these earthquake and terrorist acts scenarios, the static KPIs are calculated according to the input data for each of the scenarios and for each BET. The dynamic KPIs relating to the evacuation process are calculated by manipulating the results of evacuation simulations conditions in the 5 scenarios, for each BET, using an agent-based model developed and validated within the BE S^{2}ECURe project [35]. The main inputs from users in the scenarios are referred to users' densities and gender/age typologies in typological conditions, as assessed by the median values of previous works [36]. Nevertheless, according to the evacuation process phenomenology, in earthquake scenarios, users gather towards the centre of the square, far from debris and buildings, while, in terrorist acts scenarios, users leave the BET moving towards the access streets.

In order to obtain a uniform representation and facilitate the comparison of multiple risk scenarios, a normalization process has been performed. Many of the KPIs are presented as the output of the calculation in percentage form, encouraging the choice of normalization scale ranging from 0 (lowest risk) to 1 (highest risk). The normalization process has been done by setting a maximum risk threshold for each KPI, associated with a value of 1 on the chosen normalization scale. The normalization of each KPI is discussed in detail later in Section 3.1, as it depends on the selected KPIs.

3. Results

The following Sections presents the results of the actions taken in this paper: Selection of KPIs [Section 3.1]; Application and calculation of KPIs for BETs scenarios [Section 3.2]. A complete analysis of PIs from literature is reported in Appendix A.

3.1. Selection of KPIs

As shown in Section 2.1, the research method started from the selection of 34 PIs eligibility for KPIs for SUODs that can be ideally applied in a multi-risk perspective [4,39,50,51]. The selected PIs are summarized in Table 1 and are described in detail in Appendix B, highlighting the main characteristics and calculation method, with the aim of highlighting the aspects that determined their election as KPIs (see column in Table 1 for SMART-based assessment and final eligibility).

Table 1
SMART analysis of PIs and their potential eligibility for KPI.

ID	Name	Ref.	U.M.	S	M	A	R	T	Eligibility for multi-risk KPI
1	BI - Balance index	[23]	$[m^2/m^2]$	x	x	x	x	x	x
2	PR_d - Pedestrian route directness	[63]	[m/m]	x	x		x	x	
3	R_{RC} - Road resistor coefficient	[34]	[m/m]	x	x	x	x	x	x
4	Tr -Tortuosity	[58]	[m/m]	x	x		x	x	
5	T - Difference in path ratio	[15]	[m/m]	x	x		x	x	
6	SOSs - Temporary Secure Open Spaces	[23]	$[m^2/inh]$	x	x	x	x	x	x
7	ERD - Evacuation route distances	[23]	[m]	x	x		x		
8	A_{eff} - Effective areas surface	[15]	$[m^2]$	x	x	x	x	x	x
9	i - Friction rate	[25]	$[\%, m^2/m^2]$	x	x	x	x	x	x
10	WI - Walkability index	[23]	[%, m/m]		x		x	x	
11	v_{loss} - Pedestrian speed conservation	[24]	[%]	x	x	x	x	x	x
12	W_{SV} - Walking speed variability	[64]	[m/s]	x			x	x	
13	E – Exposure index	[4]	[%]	x	x	x	x	x	x
14	PD - Population density	[23]	[inh/ha]	x	x	x		x	
15	Cr - Congestion degree in crowded roads	[65]	–	x	x		x	x	
16	FR - Flow robustness	[66]	–	x	x		x	x	
17	C - Mean connectivity	[67]	–	x	x		x	x	
18	v - Frequency index	[67]	–	x	x		x	x	
19	ERI - Evacuation route index	[23]	[n./inh]	x	x		x	x	
20	C_A - Congestion degree in crowded areas	[65]	–	x	x		x	x	
21	c - Connectivity index	[63]	–	x	x	x		x	
22	$T_{e,95}$ - Evacuation time percentile (i.e., 95th)	[68]	[s]	x	x	x	x	x	x
23	PN - Crowd effects (i.e., number of physical contacts and falls)	[33]	[n. of items]	x	x	x	x	x	x
24	CR - Number of deaths/casualties	[69]	[inh, %]	x	x	x	x	x	x
25	CSA_{eff} - Effective CSA surface	[15]	$[m^2]$		x		x	x	
26	PI - Proximity index	[23]	[%]	x	x		x	x	
27	O_{link} - Occupancy index for the link	[15]	–		x		x	x	
28	$S_{link,SAA}$ - Safety index for rescuers' access to the link of a defined access route	[15]	–	x	x		x	x	
29	R_e - Number of evacuees (considering SAP, self-aid percentage)	[70]	–		x			x	
30	FN_{95} - Mean flow rate at the exit	[71]	[inh/s]	x	x	x	x	x	x
31	BI_d - Balance index of debris	[23][a]	$[m^2/m^2]$	x	x	x	x	x	x
32	N_{evac} - Number of Evacuees for SUOD	[70][a]	[%]	x	x	x	x	x	x
33	O_i - Obstacle friction rate	[25][a]	[%]	x	x	x	x	x	x
34	O_p - Obstacle protection rate	[62][a]	[m/m]	x	x	x	x	x	x

[a] additional integration and modification provided by this work, see above.

The final selection of KPIs for SUODs is performed according to the SMART approach shown in Section 2.1.1, as highlighted by the related column in Table 1. The selected KPIs are valid for seismic risk only, terrorist acts only or both the risks, as shown in Table 2. The combination is not related to a temporal coexistence, but to an approach to SUOD risks in contrast to SLOD risks, specifying that the possibility that terrorist acts and earthquake occur at the same times has been not taken into consideration. The final KPIs are correlated to an identification code starting with the letter K, as pointed out in Table 2.

The KPI K1 is valid only for earthquake, K11 and K12 are valid only for terrorist acts analysis. This suggests a double key of reading, from the top priority to the seismic risk, from the bottom to the terrorist acts. The KPIs from K1 to K4 are geometric indicator, this means that not directly measure user behaviour, but the effects that the built environment (and how it responds to SUODs events) has on them. The KPIs K5, K6 and K12 are static-behavioural KPIs, that study user behaviour but they are not dependent on a simulation. Finally, the remaining KPIs are directly relate to the results of the B-based evacuation simulations, as shown by Table 2, that are K7, K8, K9, K10, K11.

The method for calculating these KPIs either comes directly from the literature or has been specially modified to be adapted to the objectives of this paper. As cited in Section 2.2, each KPI has been normalized to be comparable with the others in 0 (minimal risk) to 1 (high risk) scale. This process can allow the direct comparison of multiple scenarios within the same scale, making it more functional and easier to identify possible boundary conditions affecting users' risk in the BE (including mitigation solutions). Table 2 summarizes the selected KPIs, which are then discussed below.

In the following, the KPIs in Table 2 are presented according to their calculation method and normalization procedure.

The Balance index of debris - BId (K1) is the result of a series of processing and collects in its final formulation (Equation (1)) the PIs with ID 1, 8 and 25, that are described in Appendix A. Briefly, this indicator allow us to estimate the areas that can be used to manage emergencies in the short and long term, net of the area potentially occupied by debris.

$$BId = \sum A_{deb} \Big/ \sum A_{tot} \tag{1}$$

where A_{deb} represents the area of the square occupied by debris and A_{tot} is the entire surface of the square. BId considers that the safe

Table 2
Final selection of KPI, including the identification code (ID) used also in the assessment application to the BETs, and by distinguishing reliability to Earthquake (E) and Terrorist acts (T) risks.

ID	Name (Reference work, including PI in Table 1)	Equation	Category	E	T
K1	**BId - Balance index of debris** [23][a] PI 1, 8, 25	$BId = \sum A_{deb} / \sum A_{tot}$	Static	x	
K2	**$R_{RC,tot}$ - Road resistor coefficient** [34] PI 3	$R_{RC,tot.} = \sum R_{RC} / n.\ street$	Static	x	x
K3	**V_{loss} - Pedestrian speed conservation** [24] PI 11	$V_{loss} = \sum v_{loss} / n.\ street$	Static	x	x
K4	**O_i - Obstacle friction rate** [25][a] PI 9, 33	$Oi = \frac{\sum_j (L_o \times \alpha_j)}{\sum_t L_{evt}} \times 100$	Static	x	x
K5	**SOS - Temporary Secure Open spaces** [23] PI 6	$SOS = \frac{\sum_i A_i + A_{SB}}{\sum_i (A_i \times UO_{od})} + (A_{SB} \times UO_{SB})$	Static	x	x
K6	**E - Exposure index** [4] PI 13	$E = \frac{E_E(E_T)}{E_{max}}$	Static	x	x
K7	**TN_{95} - Normalized Evacuation time (95th percentile of evacuees)** [68] PI 22	$TN_{95} = \frac{Evacuation\ time\ (95^{th})of\ users}{\max\ simulation\ time\ (600s)}$	Dynamic	x	x
K8	**PN - Crowd effects** [33] PI 23	$PN = \frac{\left(n.\ of\ physical\ contacts\ among\ users / T95\right)}{(5\%\ of\ users\ placed\ outdoors)}$	Dynamic	x	x
K9	**FN_{95} - Mean flow rate at the exit** [71] PI 30	$FN_{95} = max\left(0, 1 - \left\{\frac{\left[F95 / \sum (access\ streets\ width)\right] m)}{(1.5pp/s/}\right\}\right)$	Dynamic	x	x
K10	**R_{evac} - Number of Evacuees for SUOD from surrounding buildings in the Oss** [70][a] PI 29, 32	$R_{evac} = 1 - \frac{n.\ of\ evacuees\ arrived\ in\ a\ safe\ area}{n.\ of\ participating\ evacuees}$	Dynamic	x	x
K11	**CR - Number of deaths/casualties** [69] PI 24	$CR = \frac{n.\ of\ casualties}{n.\ of\ outdoor\ users \times (1 - TSAP)}$	Dynamic		x
K12	**O_p - Obstacle protection rate** [62][a] PI 34	$O_P = \frac{\sum_j (Ss_j \times ps_j)}{St \times pt}$	Static		x

[a] based on the work.

areas are only the ones placed in the OS, and that debris affects the quantity of such safe areas in case of evacuation. In this work, A_{deb} is determined by taking into account the area of the square occupied by the debris after the collapse of the facades (i.e. mainly focused on façade overturning according to a conservative approach), calculated using rapid methods developed in previous phases of the BE S^{2}ECURe project (see Section 2.2). Nevertheless, any other method for debris quantification in the OS can be used to the same end. Lower the BId, higher the safety level for evacuees. Anyway, free-from-debris areas should be highest as possible and, in any case, able to host all the evacuees, i.e., in non-critical crowding conditions (that is, crowding index lesser than 3pp/m^2) [15]. Due to being a ratio of areas, the BId equation always returns a value between 0 and 1, in accordance with the imposed normalization range.

The Road resistor coefficient - R_{RC} is a purely geometric indicator that measures the objective risk of the road network for the evacuation of pedestrians and has been calculated through Equation (2) for each access road to the BET. To obtain a unique index for the square, the R_{RC} values of all access roads are mediated in $R_{RC,tot}$ through the Equation (3).

$$R_{RC} = l_r / w_r \quad (2)$$

$$R_{RC,tot.} = \sum R_{RC} / n.\ street \quad (3)$$

where l_r is the length of the evacuation road and wr is the width of the evacuation road. The larger the R_{RC} is, the more difficult it is to evacuate. It is easy for victims to evacuate on short wide roads, while on the contrary, congestion will occur and certain disasters, like the stampede. The length of the street for calculate the KPI is set at 1 m to have a final normalized index variable from 0 (fluid evacuation/free road) to 1 (difficult evacuation/congested road).

The Pedestrian speed conservation - V_{loss} (K3) is an indicator defined by transforming the information about PI 11 (Table 1). In this case the speed loss during the evacuation has been estimated considering the slope of the ground, the width of the roads and the volume of traffic according to the guidelines of [24]. The traffic volume has been estimated considering the width of the roads of the BETs through the D.M. 05/11/2001 in reference to the Italian territory. The speed loss is calculated for each road v_{loss} (Equation(5)) and for the entire square V_{loss} (Equation (6)), averaging the values obtained.

$$v_f = v_i \times \theta_{\%,cons} \times St_{\%,cons} \quad (4)$$

$$v_{loss} = 1 - \left(v_f / v_i\right) \quad (5)$$

$$V_{loss} = \sum v_{loss} \Big/ n.\ street \tag{6}$$

where v_i is the Initial walking speed, assumed to be 1.4 m/s considering a pedestrian density value ≤ 0.8 persons/m^2 (free walking), v_f is the final velocity. This estimate is derived from the percentage conservation of speed versus road slope $\theta_{\%,cons}$ and traffic level $St_{\%,cos}$ (Equation (4)). Since the KPI expresses the percent speed loss, the formula returns an already normalized value. In particular, it is wort noting that the selected value for the initial walking speed is consistent with common pedestrian speed [72], and is widely assumed in many models of evacuation conditions [68]. Moreover, the assumed threshold for moving pedestrians of 0.8 persons/m^2 is be consistent with general density conditions in the BETs (typological density of 0.22 persons/m^2 in outdoors [32], see Appendix A). At the same time, this KPI hence does not consider the individual age, but it can be also very useful for quick assessment of the pedestrian speed conservation, regardless of the age typology and specific position of a given user.

The Obstacle friction rate - O_i (K4) assesses the increase in evacuation difficulty due to the presence of obstacles (both areal and linear), as described in Section 2.1. The indicator, designed mainly to assess terrorist acts scenarios, has been adapted to study seismic risk scenarios, using the same equation shown below (Equations (7) and (8)) adapted from Ref. [25].

$$O_i\ [\%] = \frac{\sum_j (L_o \times \alpha_j)}{\sum_t L_{evt}} \times 100\ [\%] \tag{7}$$

$$\alpha_j = 1 - SCV_j, \tag{8}$$

where L_o is the sum of the width of the obstacles, L_{evt} is the sum of the width of the evacuation flows and SCV, that varies from 0% (group 1 in previous classification, which represents an insurmountable obstacle) to 50% (group 2 in previous classification, indicating the possibility of jumping or bypassing the obstacle). In this way, linear obstacles can also be considered (benches, balustrades, chains, etc.). Please also compare with the friction rate PI in Appendix B.

The total width of the evacuation flows L_{evt} is defined considering respectively the escape from the square (terrorist acts) and the shelter in the centre of the square (earthquake). Similarly to K3, the output of the Oi formula here is also a percentage value and thus variable between 0 and 1.

The Temporary Secure Open spaces - SOS (K5) is an indicator adapted from PI 6 (Table 1) to expand the concept of safe area, that is the amount (in terms of surface [m^2]) of open public areas that are useful for shelter and recovery. The provision of safe evacuation areas in cities is estimated through equation shown in Appendix A. The impact derived from the presence of special buildings is included thanks to an integration of the original Equation (9).

$$SOS = \frac{\sum_i A_i + A_{SB}}{\sum_i (A_i \times UO_{od}) + (A_{SB} \times UO_{SB})} \tag{9}$$

where A_{SB} is the special building surface and UO_{SB} is the density of users for special buildings. Thus, in post-perturbation reconstruction, the quantity of open areas must remain in balance with built-up areas and population density to maintain or improve resilience. An SOS value at or above 4 m^2 per inhabitant indicates a good amount of useful open spaces after the disaster. This value has been adopted, according to international standards mentioned in the original paper [23], and acknowledging potential interactions among pedestrians [15], where the recommended threshold for both stationary and moving pedestrians is approximately 4 m^2 per person. These standards take into account communal services that can contribute to creating useful spaces for recovery purposes. In any case, the collection areas for 1 m^2 per inhabitant may also be used for short-term emergency management [23,73]. The values are normalized with respect to these limit values, so the final SOSs varies between 0 (per SOS$<$1 m^2 per inhabitant) and 1 (per SOS$\geq$4 m^2 per inhabitant).

The Exposure index - E (K6) has been adapted from Ref. [4] and described in detail in Appendix A, with the aim of evaluating evaluates the number of people in the BET both inside the buildings and in the square area, as described above. In the seismic scenario, to this amount must also be added the percentage of users who take refuge in the square, coming from other parts of the city. This percentage is called FSUP and is equal to 45% of the users of the square calculated previously. While, for terrorist acts scenarios, only users in outdoor spaces are considered at risk; all those who are inside the buildings surrounding the square are considered safe. In particular, the assessment process involves the application of the following equations.

$$E_{max}[pp] = (UO_{od} \times A_{ext} \times (1 + FSUp)) + \left(A_{sb} \times UO_{id,sb}\right) \tag{10}$$

$$E_E[pp] = \left(UO_{od} \times A_{ext} \times OI_{pp}\right) + \left(UO_{od} \times A_{detr} \times OO_{pp}\right) + (UO_{od} \times A_{ext} \times FSUp) - \left(UO_{od} \times A_{free} \times OO_{pp}\right) \pm \left(A_{sb} \times UO_{id,sb}\right) \tag{11}$$

$$E_T[pp] = \left(UO_{od} \times A_{ext} \times OO_{pp}\right) + \left(A_{sb} \times UO_{id,sb}\right) \tag{12}$$

$$E = \frac{E_E(E_T)}{E_{max}} \tag{13}$$

where, $E_{\max}$ is the maximum exposure value, against which exposure is normalized for seismic risk E_E and terrorist acts risk E_T, using the Equation (13). On this way, the value of the final Equation always variable between 0 (minimum exposure) and 1 (maximum exposure).

The Normalized Evacuation time - TN_{95} (K7) represents the time required to escape of the 95% of people who arrived in a safe zone, by excluding possible effects of outliers and latecomers who can be affected by specific surrounding conditions [35,59,72]. Social and environmental factors have an important influence on evacuation time [17]. The correct design of the architectural spaces and the recognition of wrong behaviours and waste of time by users are essential elements in order to reduce the time of exit by increasing the level of safety of the building [68]. This indicator is obtained by dividing the evacuation time at 95% of users arrived at a safe area (derived from simulation data) and the maximum simulation time (in this work, 600s) (Equation (14)).

$$TN_{95} = \frac{Evacuation\ time\ \left(95^{th}\right) of\ users}{\max\ simulation\ time\ (600s)} \tag{14}$$

The Crown effects - PN (K8) is calculated in Equation (15) to compare effective and maximum physical contacts over the evacuation time at the 95% of users arrived at a safe area (both derived from simulation data) thus normalizing the value between 0 (as minimum risk because no users' collisions) and 1 (the maximum probability of physical contacts leading to falls is reached).

$$PN = \frac{\left(number\ of\ physical\ contacts\ among\ users/_{T95}\right)}{(5\%\ of\ users\ placed\ outdoors)} \tag{15}$$

The Mean flow rate at the exit - FN_{95} (K9) is defined as the number of people passing through the exit cross-section per second and can be calculated as the number of evacuees divided by the time between the first and the last participant passing through the door direct from simulation model outputs. The flow rate is one of the most used to evaluate the efficiency of the evacuation, in fact it is an important value used in building regulations. The indicator is calculated as the users' flow corresponding to the evacuation time at 95% of users arrived at a safe area [pp/s], compared to 1.5 pp/s/m as the maximum specific users' flow according to previous experimental works [74,75]. According to Equation (16) the FN_{95} is manipulated to obtain a normalized value ranging from 0 to 1 (maximum risk), by using the reciprocal value to 1 since the flows decrease while risk is increasing.

$$FN_{95} = max\left(0, 1 - \left\{\frac{\left[F95/\sum(access\ streets\ width)\right]}{(1.5pp/s/m)}\right\}\right) \tag{16}$$

The KPI (K10 in Table 2), called R_{evac}, considers the number of people who arrived in a safe area, in respect to the number of people participating in the evacuation, according to Equation (17).

$$R_{evac} = 1 - \frac{number\ of\ evacuees\ arrived\ in\ a\ safe\ area}{number\ of\ participating\ evacuees} \tag{17}$$

Thus, the denominator of this ratio also includes the effects of possible casualties on the whole evacuation process. The value can be calculated considering the number of arrived people in respect of the initial participants to the evacuation process, thus avoiding considering people who are not affected by the process (e.g. people placed indoor in case of a terrorist act).

The number of casualties - CR (K11) that is produced over the simulation time has been normalized by the number of people participating in the evacuation. By this way, this value is based on the effective number of exposed people who take parts in the evacuation (i.e. outdoor ones for terrorist acts; all the outdoor and indoor users in case of earthquake), and excludes those who are unable to participate in the evacuation, thus assuming the impact of self-aid procedure activation depending on earthquake -SAP and terrorist act (in this case, equal to the probability to not be a casualty due to the attack [35,76]) - TSAP in the final casualties phenomena (in this work: TSAP = 88%, SAP = 50%). The value could be also calculated as in the following Equation (18).

$$CR = \begin{cases} \dfrac{number\ of\ casualties}{number\ of\ outdoor\ users \times (1 - TSAP)}\ for\ terrorist\ act \\ \dfrac{number\ of\ casalties}{total\ number\ of\ users \times (1 - SAP)}\ for\ earthquake \end{cases} \tag{18}$$

The Obstacle protection rate - O_P (K12) takes in consideration that the probability of survival to shooting attacks is increased staying out of attacker' sight, and this aspect is lectured during emergency trainings. The concept of limiting the terrorist act is sight can be applied also in other armed assaults (i.e., cold steel) and car-bombing attack. Thus, it evaluates the level of protection that an obstacle can provide to a user against a terrorist act, working as a shelter where user can hide. According to European experience in educating citizen, some urban furniture within the built environment can work as passive system of protection during the attack [51], like for example cars, trees, monuments, benches, flowerpots. For this purpose, the Equation (19) has been defined.

$$O_p = 1 - \frac{\sum_j (Ss_j \times ps_j)}{St \times pt}\ [\mathrm{m/m}] \tag{19}$$

where S_{sj} is the safe surface, defined distinctly by attack type: Attack by gunman defined by the attack hide cone, having the attacker as its vertex and determined by the shadow area generated by the j-th effective obstacle and/or frontier; Gunman attack - defined as a surface complementary to that obtained by drawing tangents from the attacker's point of origin to the first obstructions, effective with respect to the attack, and to the frontier, with respect to the direction of movement of the attacker defined as linear; ps_j represents the number of people present in the j-th safe surface, evaluated on the basis of the user density (pp/m^2) of the areas (m^2) included in the safe surface; *St* is the total area bounded by the border and crossings; *pt* is the total number of people present in the BET/square. According to Equation (19), the O_p is manipulated to obtain a normalized value ranging from 0 to 1 (maximum risk), by using the complementary of the obtained value.

3.2. Application and calculation of KPIs for BETs scenarios

This section reports the risk profiles of seismic risk (a) and terrorist acts risk (b), respectively, resulting from the application of KPIs to the identified BETs subjected to the risk scenarios. Since data are limited in terms of scenario combinations, and preliminary analysis showed that outcoming results are not normally distributed, a boxplot representation is selected for each of the indicators to show the distribution (in main quartiles) of each of the tested KPIs. Thus, the results obtained from applying each KPI to the individual risk scenarios described in Section 2.2 has been aggregated for each of the BETs (thus aggregating the considered internal layout configurations) to show the distribution of risk values. The extent and position of the box and midline clearly define the risk level of the BET, making it easy and direct to compare between them. The extremes of the whiskers represent the minimum and maximum risk value and are taken in the base case - SB and worst risk scenario, respectively, SE2 for earthquake and ST2 for terrorist acts.

K1 (BId) is a geometric indicator used to evaluate seismic risk scenarios. The main limitation lies in the way the amount of debris in BETs is estimated. According to Fig. 8, the most critical BETs are the smaller ones where buildings are structurally vulnerable to earthquake (4A and 4B); in fact, in these cases, debris can occupy the whole space.

As with K1, K2 and K3, wich are geometric indicators, but unlike K1, they apply to both earthquake and terrorist acts. The R_{RC} (K2) for earthquake measures road obstruction as a function of debris generated by building collapse, and as shown in Fig. 9a, it has a very wide range of variation, directly proportional to the magnitude of the event. Specifically, the maximum values can be attributed to the SE2 scenario with all exits blocked. The following Fig. 9 shows the $R_{RC,tot.}$ values for each BET calculated by averaging the R_{RC} of each road. For scenarios SE1 and SE2, the maximum value (i.e., 1) of R_{RC} has been assigned to roads blocked by debris. Regarding terrorist acts, it is not possible to determine whether roads are useable since no objects or debris obstructing their passage are considered in this work. Therefore, in a terrorist act, this KPI mainly depends on the general plan layout configuration and the access street width (Fig. 9b), with no additional KPI variation.

K3 (V_{loss}) investigates the environmental boundary conditions that may make users' evacuation flow management more difficult. According to the literature [24], this KPI considers road slope and traffic level. The results for BET are similar because they are all assumed to be flat, and since traffic data and road importance are not known, traffic level is also considered homogeneous in all the BETs. Fig. 10 shows V_{loss} values for each BETs, which is independent of the risk scenario and the presence of special buildings.

K4 is a static KPI, designed to assess the effects of terrorist acts and is also adapted to describe seismic risk. The O_i defines the negative influence of the presence of obstacles in an OS for the evacuation process of users, both in the phase of escape from the attack and on the way to the safe place. It appears that the use of mitigation measures with continuous linear development (bollards with chains), although limiting the probability of attack by vehicles, constitutes an obstacle to user evacuation and therefore a risk. The presence of monuments or dehors does not constitute a major obstruction, except when they are placed near the escape routes/accesses or in OS restrictions, as they decrease runoff capacity.

Since the geometric distribution of BETs is the same, from the point of view of O_i the risk remains the same whether an armed attack (ST1) or vehicle attack (ST2) is considered. In addition, as expected, the presence of debris (SE1 and SE2) is an additional obstacle to those already present. Indeed, the O_i values for the earthquake are significantly higher under the same starting conditions. Fig. 11 shows that the most critical BETs concerning O_i are those of limited size (BET 4), particularly for the earthquake, since the debris provides a great impact in terms of O_i, coming to occupy the entire OS area. Trapezoidal-shaped BETs (BET 2) also present criticality, especially when user flows are concentrated in the narrow part.

K5 and K6 are two static-behavioural indicators. First, K5 (SOS) for earthquake scenario is based on the surface area of the BET/square which is not occupied by debris, while for terrorist acts, it refers to the portion of the surface behind an obstacle, which can provide temporary shelter in case of an attack. This definition does not fully represent the complexity of real-world scenarios, but it is

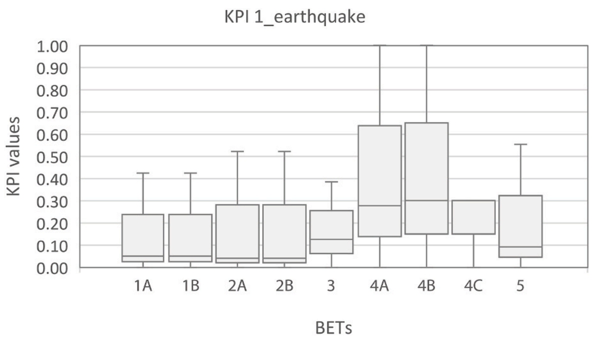


Fig. 8. Summary graphs of KPI 1 values in the three risk scenarios for the BETs.

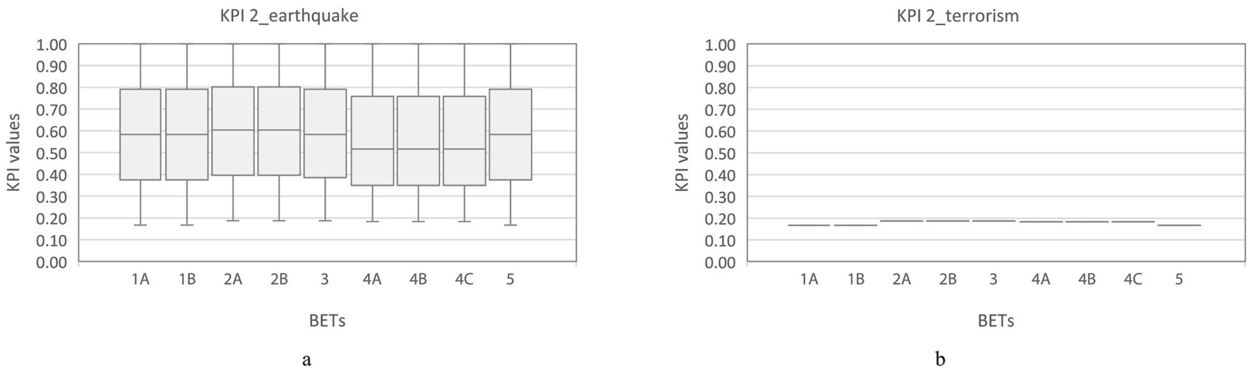


Fig. 9. Summary graphs of KPI 2 values in the three risk scenarios for the BETs.

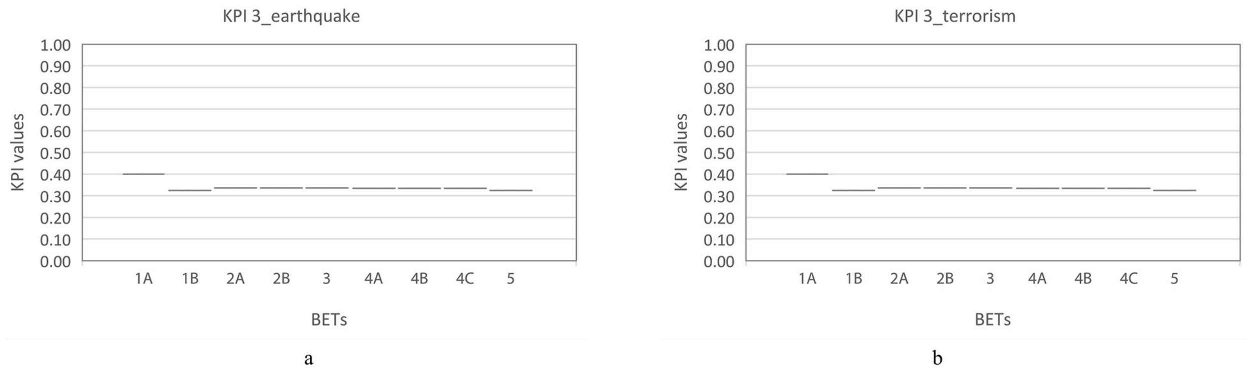


Fig. 10. Summary graphs of KPI 3 values in the three risk scenarios for the BETs.

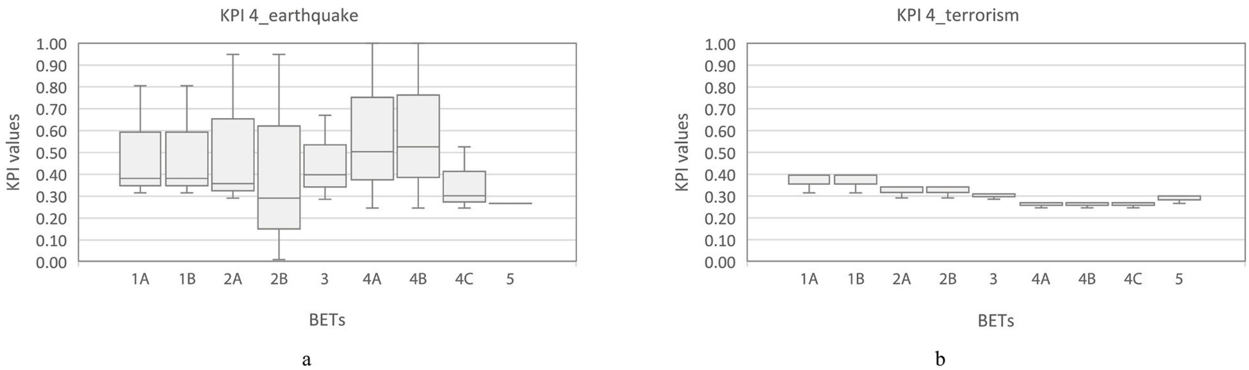
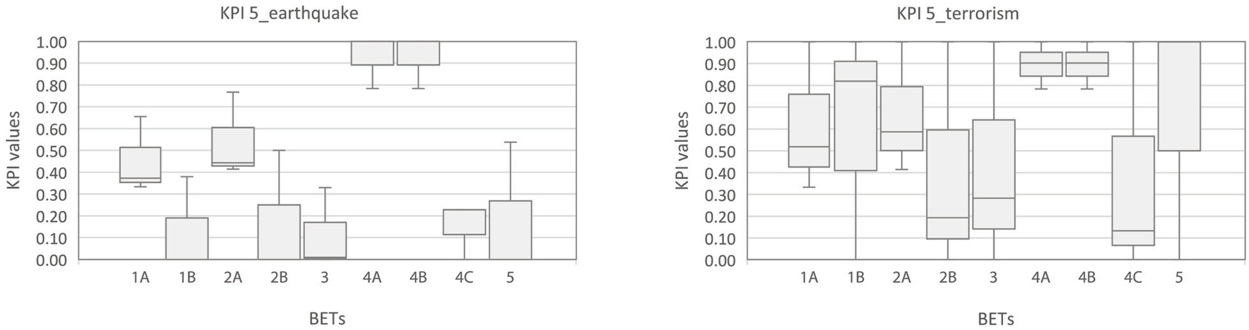


Fig. 11. Summary graphs of KPI 4 values in the three risk scenarios for the BETs.

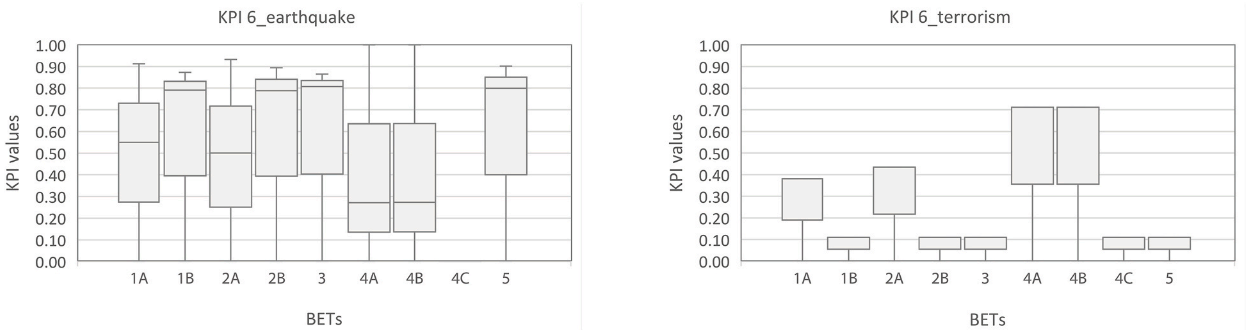
still a valuable tool to assess the risk of an OS and the potential for adopting mitigation policies which can interfere with such issues. As seen from the trend in Fig. 12, the presence of a Special Building implies the presence of more people in the BET/square, increasing the risk for the same OSs. BETs 4A and 4B (with Special Building) are definitely the most at risk due to their small size, which decreases further in the risk scenarios, even reaching negative values (indicating no safe surface availability) for SE2. The situation is different for BET 5, which, despite its size, still has limited safe areas. This scenario is a result of the assumptions made in the definition of the scenarios, where the green areas of the BET are considered fenced and therefore inaccessible to users.

K6 (E), on the other hand, is an indicator that provides a quantitative estimate of the exposed users in a BET/square about risk conditions. The results obtained for seismic risk scenarios (Fig. 13a) are generally worse than those for terrorist acts risk (Fig. 13b) for the same BET. This result is essentially due to the number of users who are potentially involved in the event. For this reason, the worst BETs are generally the largest (1A and 5) for seismic risk, since all the BET users are involved in the SUOD and in the evacuation. During an earthquake, both outdoor and mainly indoor users are exposed, while terrorist acts against sensitive outdoor targets have been considered. Therefore, the affected users are only the outdoor ones. Considering both the SUODs, Fig. 13 also shows the critical



a b

Fig. 12. Summary graphs of KPI 5 values in the three risk scenarios for the BETs.



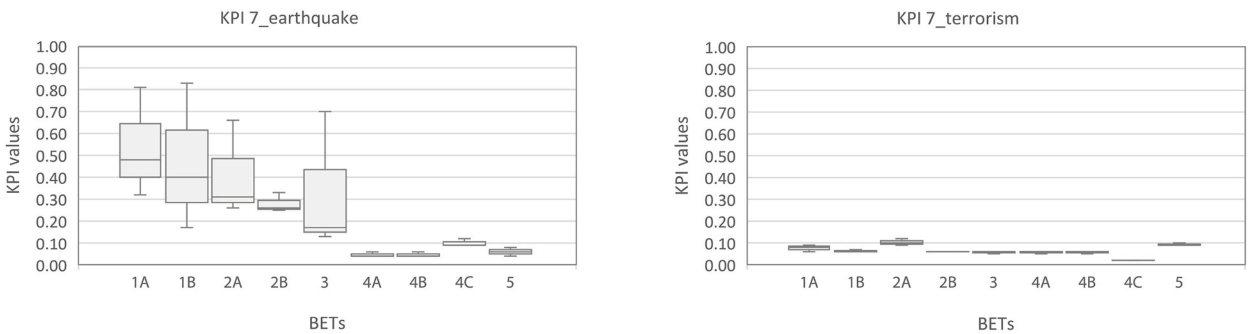
a b

Fig. 13. Summary graphs of KPI 6 values in the three risk scenarios for the BETs.

conditions of the BETs 4A and 4B due to the presence of the Special Building (large number of people) potentially spilling into a very small outdoor space. On the contrary, the other BETs are wider and, consequently less affected in terrorist act scenarios.

Regarding K7 (TN_{95}), the BETs without the special buildings show lower median values of TN_{95} than those with the special buildings, except for BET 4. In BET 4A and 4B, most people are inside the square when the earthquake occurs, enabling them to easily reach the centre of the BET itself. In contrast, TN_{95} - calculated for BET4C - is higher because most users come from the connected streets and are slowed down while entering the BET, especially under critical damage conditions. Furthermore, Fig. 14 shows an example of TN_{95} for different BETs, considering earthquake (Fig. 14a) and terrorist acts (Fig. 14b) conditions, highlighting that larger BETs are generally riskier than smaller ones, essentially because evacuation times are affected by both the length of the routes within the square and possible crowding effects.

Fig. 15 captures the values of K8 (PN) for earthquake (Fig. 15a) and terrorist acts (Fig. 15b), in the different BETs. As expected, the highest values occur for smaller BETs, as users interact in smaller outdoor spaces and, consequently increasing the possibility of physical contact while moving. On the contrary, the largest BETs characterised by the lowest users' densities (i.e. BET 1B, 2B and 3)



a b

Fig. 14. Summary graphs of KPI 7 values in the three risk scenarios for the BETs.

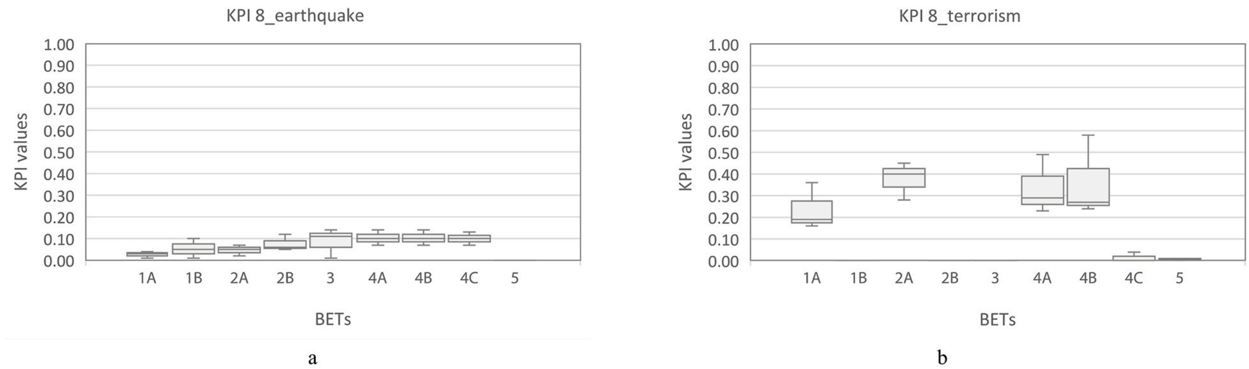


Fig. 15. Summary graphs of KPI 8 values in the three risk scenarios for the BETs.

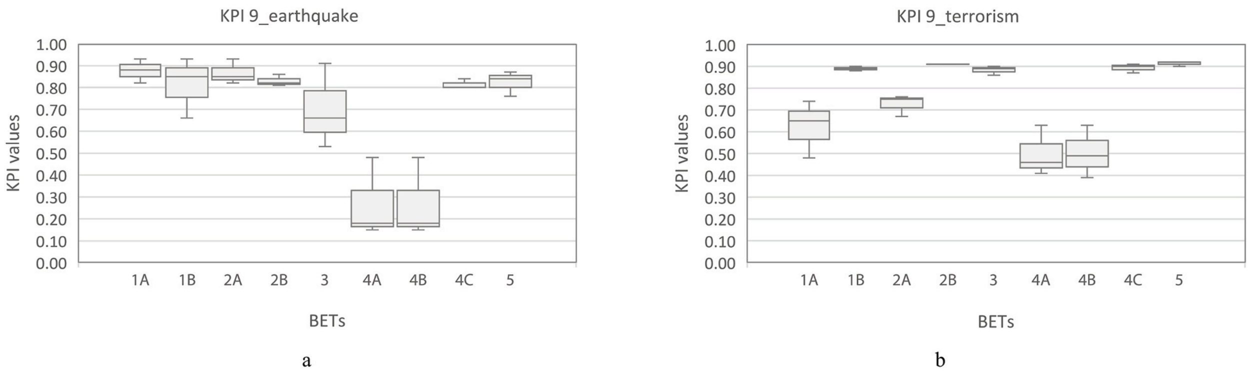


Fig. 16. Summary graphs of KPI 9 values in the three risk scenarios for the BETs.

show K8 values very close to zero in terrorist act scenarios.

The FN_{95} (K9) describes the evacuation process and specifically quantifies user flows through the BET/square. Fig. 16a shows the boxplot of KPIs for different BETs under earthquake conditions. It is worth noting that BET 4A and B, which have the most compact layout and smaller size, are essentially characterized by lower risk conditions due to FN_{95}, since most users are generated from the special building and could easily reach the centre of the square (compare with TN_{95}). BET 4A and B conditions are rather scattered, with minimum values related to minimum damage conditions. The risk increases with higher damage conditions (SE2 is more critical than SE1), while the internal arrangement (C1, C2, C3) leads to similar parameter values for both earthquakes and terrorist acts. Fig. 16b focuses on terrorist acts, showing that the riskiest conditions are related to dynamic attacks, as expected, since people should also adapt their paths and flows to attackers.

Considering terrorist acts, the users' flows effectively cross the streets linked with the square. Considering earthquake, the equation assumes, in a simplified manner, that the most important flows are those entering the square using the streets.

K10 defines the number of people successfully participating in the evacuation compared to the total number of users involved in the event. In the case of an earthquake, the BETs have similar risks, except for BET 5 (Fig. 17a). Here, the risk is higher because most of the users involved in the event are in danger. Additionally, the risk is higher because most people cannot find a safe final location, as they cannot access the green areas, and they still move to reach the centre of the square, while being limited by the presence of other individuals still arriving near the central area. In terrorist act scenarios (ST1 and ST2), K10 values are influenced by the possible direct casualties due to the attack (Fig. 17b), which increase with the users' density due to the Special Building presence, since they imply the possibility of deaths due to the attackers (i.e. upper whiskers in Fig. 17b are related to these conditions).

Indeed, K11 better focuses on these effects on users and defines the number of deaths/casualties. Movement dynamics during an attack increase the number of deaths/casualties as attackers chase users where they are positioned. This result is observed in all scenarios. The riskiest BETs are those that host the largest number of users, specifically those spaces with a Special Building, since the attack occurs where most of the crowd is concentrated. According to its definition, K11 does not cover evacuation in case of an earthquake, as it does not consider possible casualties over time due to earthquake damage.

As shown in Fig. 18, no casualties are considered for the earthquake, since no people are involved in fatal damages during the simulation time.

The values of K12 (O_P) are very high (indicating high risk) because the extent of the protection area turns out to be very small compared to the total area of the square (Fig. 19). This is compounded by a distribution of obstacles that can provide protection/hiding place during an attack, both armed (ST1) and vehicular (ST2), concerning the morphology of the squares. For example, the central

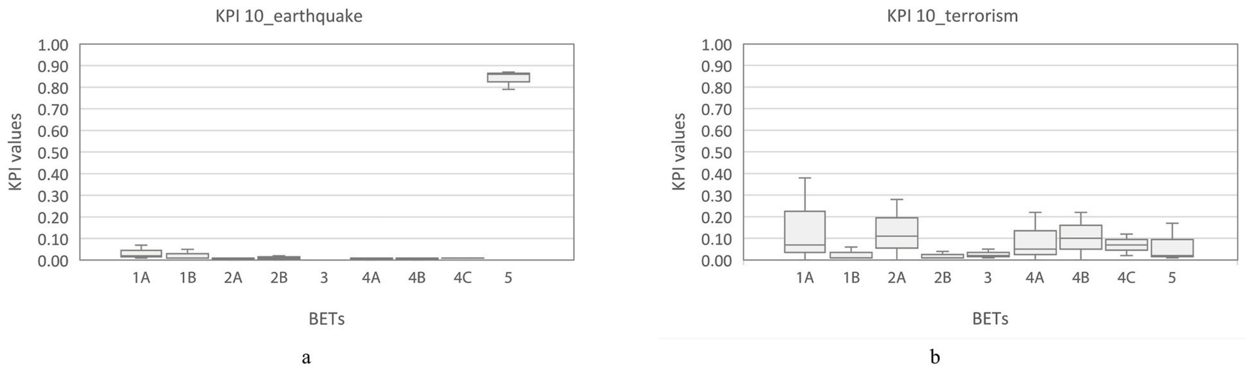


Fig. 17. Summary graphs of KPI 10 values in the three risk scenarios for the BETs.

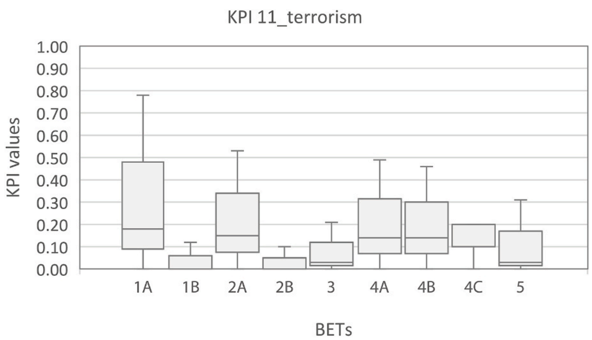


Fig. 18. Summary graphs of KPI 11 values in the three risk scenarios for the BETs.

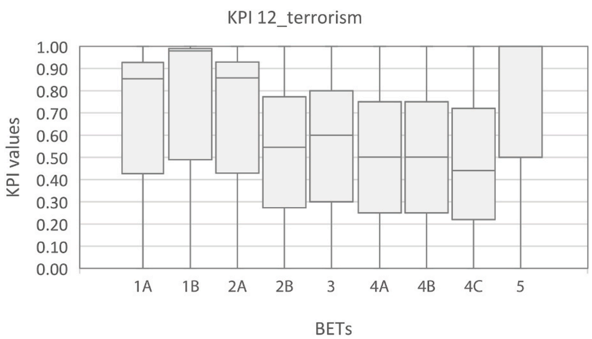


Fig. 19. Summary graphs of KPI 12 values in the three risk scenarios for the BETs.

location of the monument together with the identification of the attack points, defines the ideal screening condition. Possible attack points can be localized where crowding density is higher, specifically in correspondence of dehors (where a commercial activity is open to public users) or special buildings (e.g., a church).

However, generally, and under non-ideal conditions such as BET, a single obstacle with limited surface area (e.g., a single monument within the OS) does not provide sufficient protection to the user from the attacker. These have great importance in protection when considered as a system (multiple point elements) in the case of ST1, or systemically with other elements (edges of squares, bollards) for ST2 attacks.

4. Discussion

This study proposes an important improvement over previous literature using a set of behavioural-based KPIs, valid for the analysis of SUODs (i.e. earthquake and terrorist acts), and that can be used according to a multi-risk perspective. The contribution of this work primarily lies in overcoming the limitations of previous studies, which typically focused on applying KPIs to singular risks. Indeed, the existing literature on this topic has limited studies concerning this aspect, in particular, a limited structured knowledge of KPIs can be retrieved, due to the scattered investigations on the topic. In contrast, this work moves from performance indicators (PIs) for assessing a single risk to KPIs that can be applied both in earthquake and terrorist act risk, facilitated by an analysis of similarities among the analysed SUODs and to the SMART methodology.

The assessment focuses on the evacuation process, which is the most critical phase of managing a SUOD emergency. The overall capabilities of the approach and KPIs are demonstrated through their application to BETs which ensures: (1) a connection with recurring features of real-world case studies (since the BETs definition is based on real-world square features); (2) the ability to analyse different relevant scenarios, facilitated by typological approach in BETs definition. Thus, the defined KPIs enable the analysis of relatively simple typological scenarios like BETs as well as more complex real-world scenarios due to their versatile structure.

The discussion of results mainly points out impacts on the risk assessment in BETs (Section 4.1). Additionally, the KPIs can also contribute towards the assessment of mitigation strategies impact (Section 4.2). Lastly, limitations and insights for future works are also provided (Section 4.3).

4.1. Impacts on the risk assessment of archetypes of open spaces (BETs)

As outlined in Sections 1.2 and 2.2, these BETs can be considered as archetypes of real world squares and are characterised by reliable (albeit simplified) main morphological, geometric and constructional features, without directly representing real case studies. It is important to note that the results presented in this study are an abstraction of reality and should be treated as such. Accordingly, the validation of the has been conducted not from an absolute perspective, but by comparing the different scenarios.

Considering the overall picture, a strong relationship emerges between the effects of SUOD risks, user behaviour and the specific characteristics of the BETs. The risk characterisation is shaped by the interaction of all the indicators, with each BET distinguished by one or more KPIs according to its unique features. As a result, the seismic risk across the analysed BET appears rather homogeneous and characterized by a progressive worsening as a function of the increase in debris in the different scenarios (refer to box-plot graphs in Section 3.2). During earthquake evacuations, users' behaviour is essentially consistent across BETs, since all the users tend to converge towards the centre of the square and main interactions with the built environment and its damage is limited to the boundary areas. Conversely, the terrorist acts assumes a more variable configuration essentially based on the presence of the special building, which leads to an increase in exposure and influences the dynamics of the attack, directing it towards the most crowded point.

Considering the differences between the analysed BETs, it can be seen that the main criticality in the larger BETs (BET 2, BET 3 and BET 5) is the length of the evacuation routes; a longer evacuation route implies greater difficulty in arriving at a safe area, leading to a higher risk. Conversely, in BETs with restricted outdoor spaces or areas (e.g., BET 4), the main problem is the limited availability of safe areas. The available free area within the BET can be significantly reduced by the presence of fixed furniture (e.g., monument, bollards, dehors) and, in the case of seismic risk, also by the presence of debris, which may, in the worst case (e.g., SE2), occupies the entire surface.

4.2. Moving towards mitigation strategies assessment by KPIs

The definition and application of KPIs can also serve as supporting tools to identify a set of mitigation strategies and to elite the best practices, in view of the peculiar phenomena they assess. Indeed, Temporary Secure Open spaces (K5) and Mean flow rate at the exit (K9) are more related to the geometrical aspects of the OS, highlighting the influence of dimension and, generally, the accessibility of the OS. Specifically, Temporary Secure Open spaces (K5) evaluates the accessibility, linked to the extension of the safe area, relevant in seismic risk assessment, while the Mean flow rate at the exit is strictly related to the length of evacuation routes. Giving an example, the presence of a central green area in the BET 5 determines inaccessibility during a SUOD event and reduce the temporary secure area. These two performance indicators can assist in planning layout modifications or emergency strategies. Nevertheless, the outputs of simulations of pre-retrofit and post-retrofit may be compared to better understand the level of effectiveness of mitigation strategies.

Alongside the definition of a set of mitigation strategies, the investigated method can also be applied to measure the effectiveness of a single one. Planning the installation of urban furniture or other types of elements within the open spaces has effects on the variation of the planimetric and altimetric configuration of the OS. These strategies are designed to guide users' movements, manage evacuation flows, define areas with high attendance, and serve as temporary sheltering elements in the event of a terrorist action. Among urban furniture, engineered planters can prevent the access of vehicles within the open spaces, providing protection from terrorist attackers. The evaluation of the location, dimension, and layout of planters is supported by the quantification of the Obstacle protection rate (K12). Conversely, their influence as obstacles to evacuation routes toward the centre of the square must be assessed in earthquake scenarios.

Because of these above-mentioned considerations, future research will consist of experimenting with the developed KPI to assess the effectiveness of different solutions and to identify the most effective strategies, both for single and multi-risk scenarios. Moreover, further investigation will be performed to include the rescuers' perspective in the selection of a set of KPIs, valid in immediate post-evacuation phase, as assessment tool of straightforward arrival of first responders in the OS. This action can contribute to a multi-perspective assessment of OS risk and mitigation scenarios.

4.3. Limitations and insights for future works

The current work relies on the KPIs application to the BETs, and thus results can be affected by the typological conditions assumed for scenario creation. First, concerning the assessed OSs, insights of this work may be specific to the Italian context, and the assessed historical BETs may not directly reflect contemporary OSs. Moreover, the authors are aware that the set of scenarios is limited also in terms of hazard scenarios and users' crowding and vulnerability, although it does not affect the capability demonstration and the general insights on the investigated archetypes of OSs.

Concerning seismic risk, building vulnerability assessment has been simplified by mainly modelling some relevant scenarios of debris effects on the OSs. Additional (intermediate) debris conditions should hence be analysed by future works, by also incorporating more complex seismic scenarios that can consider variations in building damage within the same built environment. The analysis should go beyond façade overturning adopted in this work according to previous approaches [4] and include a comprehensive assessment of the building seismic vulnerability also using data by constructive typology.

Concerning terrorist acts, this work considers only two relevant typologies of attacks, a limited set of point of these attacks, and the concurrence in the position of perpetrators within the BET. Therefore, it is necessary to consider other types of terrorist acts, such as bombings, gun attacks or combined ones (bombing plus armed assaults), and several "modus operandi" based on spread positions of perpetrators, since they may have wider and more complex effects on the crowd.

Concerning user-related factors, specific intended uses and crowd/individual users' features should be investigated. For instance, this work considers the presence of special building or dehors as crowded areas and attracting targets for perpetrators, but other facilities and intended uses (e.g. commercial space, market areas, mass-gathering events), which could locally modify the behaviour and distribution of users and change the dynamics of risk, have been not considered. Vulnerable users (e.g. by age, gender, motion and sensory abilities) could be included in the crowd, so as to verify the impact of such variables on the whole evacuation process through the KPI-based assessment.

From a methodological point, it is important to note that the definition of risk scenarios could also consider other assessment methods in addition to those provided by this work. In fact, the overall workflow adopted by this work is flexible enough to support this task, which can increase the reliability of the input conditions depending on the specificity of the considered SUOD, built environment and users. Thus, alternative assessment procedures and tools can be employed to describe the scenarios, as in Table 2, as long as they can provide related compatible data.

Indeed, the proposed methodology offers interesting perspectives for future work. The use of typological scenarios allows for the highlighting of general issues related to the effects of SUOD risks in OSs and on the users within them. These aspects can be quickly assessed through application to BETs, guiding designers in the preliminary evaluation of real-world scenarios and conducting in-depth analysis and tailor-made solutions based on the specific features of real-world case studies. Therefore, future investigations should shift their focus from risk assessment to risk mitigation strategies analysis, using the developed KPIs for quick assessment. Various parameters can affect seismic risk and terrorist acts, including the presence of mitigation elements such as barriers and bollards (compare Section 4.2). Further simulations and evaluations of KPIs in the same BET can be considered, resulting in different typological conditions and different simulation input scenarios, which may also correspond to different risk mitigation scenarios. These tasks are in line with the general goals of the BE S^2ECURe project, too.

Moreover, this work focuses on the selection and capability demonstration of KPIs, but further efforts are needed to combine into risk metrics. It is important to note that a single KPI may have different relevance based on the analysed risk. Therefore, two separate metrics could be developed for each SUOD, and the priority of each KPI can be linked to a specific KPI weight in the whole metric. Observing each KPI by itself can lead to analysing and adapting the BE depending on a specific phenomenon, while the overall metric can provide a general overview of different risks and conditions, pursuing a short comparison among selected scenarios.

In addition, modifications to KPIs can enhance the representation of microscopic issues in evacuation processes and improve the assessment of user behaviour. In particular, Pedestrian speed conservation (K3) actually assumes standard conditions in the walking speed, although the simulation model can reproduce individual features affecting this parameter. K3 could hence be calculated in reference with specific initial age-dependent walking speeds. Moreover, an advanced (i.e. weighted) assessment could be also performed by merging K3 effects on different typologies of users, or the worst age-dependent values could be selected to describe worst risk conditions, according to a conservative approach. The formulation of the Obstacle protection rate (K12) could be also improved introducing a dynamic state, in order to identify the peak of the value according to a not-steady condition of crowds and attackers. This approach allows to consider users' variable behavioural preparedness to terroristic act in running and hiding activities. In this manner, the KPI would measure the effectiveness of protection feature of obstructions, and the effectiveness of users' training in a combined manner.

5. Conclusions

The challenge of assessing SUOD risks, such as earthquakes and terrorist acts, in open urban spaces is closely related to the interaction between the specific risks, characteristics of the BE, and user behaviour. To address these factors, this work presents a rapid risk assessment methodology based on the use of behavioural KPIs relevant to BE open spaces, such as squares. The proposed method enables the assessment of the characteristics of each analysed SUOD, using consistent indicators. A preliminary application of the methodology considers the BET, which represent archetypes of Italian squares in historic urban areas. BETs are characterized according to recurring geometric, morphological, and constructional features identified through statistical analysis of actual squares. These features capture simplified yet reliable scenarios.

Within the context of the selected BET, the results show that the presence and quantity of debris is the determining variable in the definition of seismic risk, influencing the availability of the free surface (and safe area) and the movement of users. In the case of terrorist acts, the impact of risk is determined by the distribution of obstacles that can provide temporary shelter and escape routes.

The application of BETs stands out as a significant strength of this study. It allowed to experiment and compare a wide range of established and reliable scenarios, enabling the identification of both strengths and critical issues in each configuration. Moreover, it permits preliminary assessments of effectiveness and can be replicated in real contexts of the built environment, offering considerable support to designers and local governments in risk assessment and guidance on the selection of effective mitigation solutions. In BE, preventive risk assessment can guide the timely development of effective and environmentally friendly mitigation measures.

The high stability and flexibility that characterise the method proposed in this study, make it also suitable for implementation across different contexts of the BE, including those of other countries, provided that the necessary information regarding the geometry of the space, the characteristics of the risk and the presence of users are available or calculable.

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CRediT authorship contribution statement

Alessandro D'Amico: Conceptualization, Data curation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Gessica Sparvoli:** Data curation, Formal analysis, Validation, Writing – original draft, Writing – review & editing. **Gabriele Bernardini:** Conceptualization, Formal analysis, Validation, Writing – original draft, Writing – review & editing. **Silvana Bruno:** Formal analysis, Validation, Writing – review & editing. **Fabio Fatiguso:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Edoardo Currà:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Enrico Quagliarini:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Conceptualization of the research, E.C., A.D., G.B., E.Q. and F.F.; conceptualization of the paper, A.D. and E.C.; methodology, A.D.; validation, G.B., A.D., G.S., S. B. and E.C.; formal analysis, G.S. G.B., S.B.; data curation, A.D. and G.S.; writing-original draft preparation, A.D., G.S. G.B.; writing-review and editing, A.D., G.S., G.B., S.B., F.F., E.Q. and E.C.; supervision, E.C., F.F., E.Q.; project administration, E.Q., E.C., F.F.; funding acquisition, E.Q., E.C., F.F. All authors have read and agreed to the published version of the manuscript.

Appendix A. Simulation model overview

The simulation model has been developed and verified by previous works within the BE S^2ECURe project [57,58], using the open-source NetLogo platform (version 6.2.0), which enables to combine agent-based modelling with a cellular automata approach [77]. This choice allows the fast assessment of evacuation behaviours by distinguishing the features of OS and SUODs effects, as well as by identifying different typologies of users with specific individual motion rules.

The cellular automata use a discretization grid with a side size of 50 cm, using squared cells, being comparable with the users' dimension [78]. Each cell is characterized to represent the OS main composing elements (outdoor pedestrian areas, carriageways, obstacles and street furniture, specific outdoor intended uses such as those of dehors, buildings facing the OS including the special building, the access streets) and the effects of the SUODs on the OS and its users (i.e. earthquake-induced debris from buildings; attack area in terrorist acts).

According to the possible functions in the OS [38,79], users are randomly generated depending on the intended uses of the cells, by considering passersby (placed outdoors in cells representing pedestrian areas), customers of outdoor commercial areas (placed outdoors in cells representing dehors), visitors of the special building, where present (placed outdoors in front of the building, waiting to enter it), building occupants (placed in buildings) and users occupying areas of surrounding streets (ideally placed at the access streets). The number of generated users is calculated as the multiplication between the experimental users' density in the BETs context (0.22 persons per m^2 of outdoor areas) and the outdoor areas of the BET, plus 480 persons for the occupancy of the special building, when present [36]. The percentages of users by typologies are derived from experimental values in the BETs context, that is 20% of passersby, 4 % of customers, and thus 76% of building occupants, while the number of users [36]. In case of earthquake simulation, an additional 40% of users are associated to those occupying areas of surrounding streets and then entering from the access streets.

Once the users are generated, the model simulates the evacuation process in relation to the phenomenology of the specific considered SUOD. In the event of a terrorist act, users in the buildings remain inside, considering that they are protected from the attackers, while those outsides are moving to leave the square, thus heading towards the access roads [21]. Outdoor users placed in the attack area can suffer damage and cannot participate to the evacuation (probability arbitrarily assumed equal to 50%) [35]. In the event of an earthquake, all people try to reach the OS and move away from the buildings. Users already present in the OS, in outdoors, try to directly reach the central areas of the OS itself, while users evacuating from the access streets and the OS buildings first move far from buildings and then try to reach the center of the OS. Moreover, users generated inside or in the debirs area have an opportunity to participate in the evacuation of 88%, thanks to previous experimental studies on procedures for autonomous participation in the post-earthquake evacuation [70]. Users are not allowed to end the evacuation in the cells affected by debris, tending to move away from them, considering these cells can be overpassed while moving.

According to experimental values [46,75,80], the speed of the users *Vi* [m/s] in evacuation motion depends on the considered SUOD and on the users' density *UD* [persons/m^2] (calculated according to the extended Moore neighborhood method), according to Equation A.1. Beyond the density thresholds in Equation A.1, the model considers a linear decay of *Vi* up to 0 m/s at critical density for evacuation stop (about 6 persons/m^2). The typology of users by age is also considered according to statistics on BETs (random assignment of features to the users) [36] and associated to a speed reduction coefficient VR_{age} [−], which is equal to Refs. [35,80]: for hand-assisted toddlers (0–4 years), 0.53 (4% of users); other parent-assisted children (5–14 years), 0.87 (9% of users); youngsters (15–19 years), 1.00 (6% of users); adults (20–65 years), 0.87 (64% of users); elderly (70+ years), 0.67 (18% of users). A random error (Gaussian distribution, standard deviation of 0.7 m/s) is also associated to represent variations in *Vi* at the individual level. Moreover, when local density≥3persons/m^2, the model evaluates if users can be involved in falls and stop the evacuation in view of physical contact between users, by considering a probability of 5% [35]. When a user falls down at the ground a temporary interruption of the evacuation process for a maximum of 30s (uniform random distribution) is considered.

$$Vi\left[\frac{m}{s}\right] = \begin{cases} terrorist\ act: VR_{age} \bullet (2.50 - 0.72) \bullet \left(1 - e^{-0.14\bullet\left(\frac{1}{UD}-\frac{1}{2.67}\right)}\right) + 0.72\ for\ UD \leq 2.67 persons\Big/m^2 \\ earthquake: VR_{age} \bullet (3.29 - 0.71) \bullet \left(1 - e^{-0.8\bullet\left(\frac{1}{UD}-\frac{1}{5.30}\right)}\right) + 0.71\ for\ UD \leq 5.30\ persons\Big/m^2 \end{cases} \quad (A.1)$$

While moving towards safe areas (access streets for terrorist acts; center of the BET for earthquake), users choose their own path through the selection of cells of the BET, according to attraction maximization criteria depending on the factors shown in Equation A.2 [33]. The attraction of a single cell *c* at the time of simulation *t Ac,t* [−] varies between 0 and 1. *Ac,t* depends on two parameters that do not vary over time, which consider the morphological configuration of the BET and the safe area to reach: *Fc,t* [−] expresses the normalization of the distance from *c* to the nearest safe area, and assumes maximum value close to the safe area itself; *Oc,t* [−] represents the normalization of distance from *c* to the nearest building, monument or street furniture, and takes minimum value close to the obstacle. On the other hand, two factors are variable in time: *Pc,t* [−] is based on the normalization of users' density, and grows with the density decrease; *Rc,t* [−] expresses the normalization of the distance from *c* to the source of the risk (debris or attack area). Each factor is associated with a relative weight *w*, variable between 0 and 1, to modify the incidence of the parameter at the behavioural impact. In this work, $w_P = 0$, $w_F = 0{,}9$, $w_R = 0{,}1$, $w_O = 0$ for terrorist act, so as to focus on the effects of the SUODs (proximity with attack area and debris presence) in combination with the preference for path length minimization.

$$A_{c,t} = w_P \bullet P_{c,t} + w_F \bullet F_{c,t} + w_R \bullet R_{c,t} + w_O \bullet O_{c,t} \quad (A.2)$$

The selection is performed according to the features of the cell. Features that do not change over the simulation times are: (a) the distance to the closest exit *Fc,t* [−], which assumes a maximum value for the cells nearby an exit cell; (b) the distance towards the nearest obstacle *Oc,t* [−], which assumes minimum values the cells nearby a building or monument cell. Features that vary over time are: (a) the risk level *Rc,t* [−] which assumes a minimum value in the cells of the attack area where the terrorist act occurs; (b) the pedestrian density *Pc,t* [−], which is calculated by applying the extended Moore neighborhood method for each user, and considering just free-of-obstacles cells [71]. In particular, $P_{c,t}$ varies during the simulation time depending on users' positions. *Fc,t, Oc,t, Rc,t,* and *Pc,t* range from 0 (more critical conditions) to 1 (ideal conditions). At each simulation step, users evacuate by selecting the neighbouring cell having maximum attraction value *Ac,t* [−] [78], calculated as combinations of the aforementioned features according to Equation A.2. Different weights *w* [−] are introduced in Equation A.3 to account for different behavioural responses in path selection, being in the range 0–1, and being their sum equal to 1.

$$Ac,t = w_F * Fc,t + w_O * Oc,t + w_R * Rc,t + w_P * Pc,t \quad (A.3)$$

In case of terrorist act, attackers are also simulated depending on the types of attacks (see also Section 2.2) [32,35]: in the armed assault (ST1), they move to chase and damage neighbouring users placed in their attack area at a distance of about 1 m; in the vehicle attack (ST2), the vehicle to crash a target running over the users placed along its linear trajectory placed in its attack area at a distance of about 3 m. Users considered as casualties due to the attack or to earthquake debris and damage stop the evacuation and exit the simulation.

The evacuation process ends when all the users reach one of the safe areas in case of a terrorist act, or decide to stop in the central area of the BET in case of earthquake (thus maximizing *Ac,t*), or even when the maximum simulation time is reached, in both cases. In this study, the maximum time of simulation is 600s, compatible with the times of intervention by rescuers towards the square in an urban scenario.

Appendix B. Selection and summary definition of PIs from literature

Performance Indicators (PIs) reported in Table 1 are herein discussed considering their definition according to literature works. Each PI is associated to the realted ID in Table 1, while references to selected KPIs are also reported according to Table 2. The Balance index - BI (**ID 1**) by [23] indicates a city's open spaces system, consisting of the network of streets, parks and square that are activated after disastrous SUOD event, mainly in case of earthquake. In such a condition, users evacuate built areas (that is, the buildings) and move towards the urban open spaces (that are streets, parks, squares) where safe areas are placed. As a consequence, the ratio between the quantity (the area [m^2]) of open spaces and built areas should be ideally maximized to ensure a direct support to the process and reduce the interferences with the build areas. This indicator allows us to estimate such ratio through the Equation B.1 and then to evaluate the management of emergency phases in the short and long term, considering the availability of outdoor (unbuilt) areas.

$$BI = \sum A_{ub} \Big/ \sum A_b \ \left[\mathrm{m}^2 / \mathrm{m}^2\right] \tag{B.1}$$

where A_{ub} is the unbuilt useful area of the BET and A_b is the built area of the BET. In view of its definition, BI depends on the morphology of the urban fabric, and the original work essentially uses this PI to compare conditions before and after reconstruction of urban scenarios due to a disaster impact [23]. Nevertheless, the same principle on BI definition can be used to compare conditions due to a variation of the exposed users' number. For instance, "the population increase" can be "balanced by the improvement in open spaces that is positive for the resilience [23]. BI could be also extended to compare different BEs rather than the same BE in different conditions: the safer BE will be the one with the higher BI value.

The BI has been integrated and improved to include the effects of debris, then related to earthquake evacuation conditions [15], combining the Effective areas surface - A_{eff} (**ID 8**) and the Effective CSA surface - CSA_{eff} (**ID** 25) in Table 1 through the difference between the CSA (Codified Safe Areas, that are the emergency assembly points defined within the evacuation plan) considered net of courtyards and other areas not accessible, and the area occupied by debris (A_{deb}) in the open space and along the links [m^2], according to Equation B.2.

$$A_{eff} = CSA - A_{deb} \ \left[\mathrm{m}^2 / \mathrm{m}^2\right] \tag{B.2}$$

It is worth remarking that Safe areas are, with reference to the BET application, the access streets to the square for terrorist act evacuation (users moving far from the attackers and leaving the square) and the free-of-debris area at the center of the square for seismic evacuation (users entering the square and moving far from buildings and debris). Moreover, Safe Areas should contain ideally evacuees by avoiding overcrowding and, in case of seismic evacuation, interactions with debris should be minimized if not removed [15].

By combining all these aspects, a new indicator has been defined, which is more suitable for assessing seismic risk. This new PI is named BI of Debris - BI_D (**ID 31**) has been elected as a KPI (K1 in Table 2) and its discussion has been outlined in Section 3.1.

The Pedestrian Route directness - PRd (**ID 2**) [63] defines the ratio between the actual distance of a route in the urban space (D) and the geodetic (or straight-line) distance (d_l) between its origin and destination (Equation B.3).

$$PRd = D \big/ d_l \ \left[\mathrm{m} / \mathrm{m}\right] \tag{B.3}$$

The distance value changes according to the initial position of the users. As a consequence, PRd calculation can be very expensive, being based on values for each user, and this goes against the general possibility to perform quick assessment by using KPIs. In the event of an evacuation, this parameter can be used to define the capacity of an urban system to allow direct movement from the vulnerable position to the safety zone [39].

The Road resistor coefficient - R_{RC} (**ID 3**) [34] is the second KPI defined in this work (K2 in Table 2).

The Tortuosity index - Tr (**ID 4**) [58] expresses the difference between the minimum linear path length and the average evacuees' path length, highlighting the criticalities along the path and the microscopic interactions between the evacuees and the surrounding built environment (i.e. for pedestrians' and debris avoidance, for pedestrians' behaviours on the links) [19].

Difference-in-path ratio - T (**ID 5**) [15] represents the average length ratio between the effective evacuation path and the ideal one for all evacuees arriving at the Safe Area. The effective evacuees' paths are calculated for each evacuee considering its movement trajectory from the starting point to the selected safe area, and thus it relies on evacuation simulation data. The ideal path is calculated through a straight line connecting the initial point and the selected safe area, and thus it is assessed according to a shortest distance criterion. The ratio between the effective and ideal path is calculated for each evacuee, and then, the mean is calculated. T hence assesses the complexity of the evacuation path by measuring the frequency of pedestrians altering their course (e.g. to avoid pedestrians and debris, for example, due to walking behavior on links). Thus, in some terms, this index is similar to the Tortuosity index, although they rely on two different issues in evacuation motion.

It is worth noting that, in pedestrian route directness assessment, all evacuation paths are considered, and the geodetic distance varies according to the position of the users with respect to the assembly point. In tortuosity index and Difference-in-path ratio assessment, the average length of all evacuation routes is compared with the shortest route, considering additional criticalities such as interactions between people and the presence of debris.

The temporary Secure Open Spaces - SOSs (**ID 6**) [23] expresses the amount (in terms of surface [m^2]) of open public areas that are useful for shelter and recovery calculated with the Equation B.4.

$$SOSs = \sum SOS\ areas \Big/ inhabitants \ \left[\mathrm{m}^2 / \mathrm{inh}\right] \tag{B.4}$$

Thus, in post-evacuation reconstruction, the quantity of open areas must remain in balance with built-up areas and population density to maintain or improve resilience, especially for possible future SUODs. An SOSs value at or above 4 m^2 per inhabitant indicates a good amount of useful open spaces after the disaster.

Cities subject to earthquakes (and more generally to SUODs) must be equipped with an effective evacuation system, equipped with well-known, accessible and safer escape routes.

The KPI K5, presented in Section 3.1 is an adaptation of this indicator.

In this regard the Evacuation route distances - ERD (**ID 7**) [23], defines the distance of evacuation routes from the farthest.

The Friction rate - i (**ID 9**) [25] considers the reduction in the evacuation speed of evacuees caused by micro-vulnerabilities (due to, e.g., inappropriate use, inadequate maintenance and problems related to the design of evacuation routes) detected along the evacuation path, also allowing a comparison of them and to determine their relative degree of vulnerability. Micro-vulnerability has been categorized into one of the following groups [25]: (1) obstruction or reduction in available evacuation spaces, due to fixed obstacles such as outdoor walls, trees, monuments, debris, fixed seats, fences, shrubs and hedges; (2) sudden alterations in surface levels, which can even be jumped or bypassing by users while moving, such as stairs, uneven surfaces, and bollards with chains which are slightly raised from the ground; (3) noticeable variations in surface roughness, which essentially imply a reduction of users' speed, such as green areas (if accessible by users, thus not fenced) and cracked sidewalks. In this work, micro-vulnerabilities of group (1) and (2) have been considered due to they effective impact to the movement of crowd in respect to group (3), considering variations in the layout of the open space and the typological elements characterizing the BETs [42,67,73]. The quantification of the micro-vulnerabilities and the obstruction levels of the evacuation routes is defined through a proposed friction rate, defined as in the Equations B.5-B.6.

$$i = \frac{\sum_j S_{m_j} \times \alpha_j}{S_r} \times 100\ [\%] \tag{B.5}$$

$$\alpha_j = 1 - SCV_j, \tag{B.6}$$

where S_r is the surface area of the analysed evacuation route, and the micro-vulnerabilities are described by:

- Its surface area along the evacuation route Sm [m^2], which is equal to the related area projection on the ground;
- A speed reduction factor, that is the coefficient α, which depends on the speed conservation value (SCV), indicating the percentage of the maximum speed sustainable on a particular surface, and thus on the specific micro-vulnerability group. In detail, SCV values are 0 for group (1), 0.5501 for group 2 and 0.9091 for group (3).

To make Álvarez's proposed method more useable even for narrower environments such as streets and alleys, Equations B.5-B.6 are changed to Equations (7)-(8) with the name Obstacle friction rate - Oi (ID 33), already presented in Section 3.1 in defining KPI K4 Table 2.

Another parameter that can affect the evacuation speed is the Walking speed variability - Wsv (**ID 12**) [64] that considers the individual speed adjustment during the evacuation in view of the surrounding pedestrian dynamics, thus including density effects. In correlation with the simulations for the BETs, this work considers that the walking speeds are directly considered within the simulation model [35].

The Walkability index - WI (**ID 10**) [23] evaluates the percentage of streets and pedestrian walkways with the Equation B.7.

$$WI = \left({}^{l_w}\!/_{l_{tot.}} \right) \times 100\ [\%] \tag{B.7}$$

where l_w is the length of walkways, $l_{tot.}$ is the total streets length and multiplying the ratio by 100 gives a percentage value always between 0% and 100%.

In the context of a crisis due to rapid disasters, urban morphology strongly influences the evacuation times of users. The PI Pedestrian speed conservation - v_{loss} (**ID 11**) [24] that has been elected as KPI (K3 Table 2) considers morphological and geophysical aspects which affect this aspect, according to factors including land use and terrain slope. Particular attention should be paid to the assessment of the roads, the width and length of evacuation routes and the volume of traffic.

The Exposure index - E (**ID 13**) [4] is defined in terms of human lives (number of persons) and assesses the spatio-temporal distribution of users depending on the hosted activities in both outdoor and indoor areas (i.e. facing buildings, because of the correlation between their intended use). The exposure is assessed following the innovative procedure proposed by Ref. [4] with the Equation B.8 where individual vulnerability aspects are taken into account by considering three different age categories.

$$E = \sum_i U_{OD_i} \times x_{\%i} \times w_i\ [\%] \tag{B.8}$$

where U_{ODi} are the normalized user occupancy in the given time period, $x_{\%i}$ are the percentages of the related age group within the population of the OS in the HBE and w_i is the weighted percentages of the related age group. This PI has been adapted to be elected as KPI (K6 in Table 2).

The Population Density - PD (**ID 14**) [23] that refers to the number of inhabitants per area:

$$PD = {}^{inhabitants}\!/_{area}\ [\text{inh / ha}] \tag{B.9}$$

considering that a high PD means low system resilience. This parameter suggests that in a resilient city the congestion degree in crowded roads - Cr (**ID 15**) [65] provides an estimate of the crowding condition along evacuation paths following a SUOD emergency, in order to plan the most functional evacuation route. This is influenced by geographical characteristics, such as road width, and possible degree of collapse of buildings and is calculated with Equation B.10.

$$C_r = \sum \left(occurrences\ of\ path / _{number\ of\ path} \right) \tag{B.10}$$

The Flow robustness - FR (**ID 16**) [66] is measured by computing the flow robustness defined as:

$$FR = n_f / n_{tot.} \tag{B.11}$$

where n_f is the number of flows and $n_{tot.}$ is the total number of possible flows in a network.

A new flow strength value is calculated each time a node is removed from the system (either due to debris, destruction, etc.). The obtained value is normalized with the total number of flows of the network, which is $n\ (n-1)$, where n is the number of nodes in a network. A further method is to measure the effect of interruptions using indices.

Mean connectivity - $\overline{C}$ (**ID 17**) [67] represents the number of alternative paths within the whole grid and is the ratio between the connectivity values and the total number of segments in the set B.12.

$$\overline{C} = \frac{1}{n} \sum_{i=1}^{n} C_{\theta,i} \tag{B.12}$$

The values range from 1 to n, being n the total number of segments, and are high in case of a massive presence of alternative paths; $C_{\theta,i}$ is the measure of angular connectivity and is the sum of the total number of angle turns to a root segment i.

High values of the mean connectivity guarantee the presence of alternative paths in the grid. Instead, the Frequency index - v (**ID 18**) [67] represents the distribution level of the shortest paths in the grids. The v is expressed by the ratio between the maximum actual choice $Ch_\theta(x)^{max}$ in the set of segments and the maximum value it could virtually reach v^{max} B.13.

$$v = \frac{Ch_\theta(x)^{max}}{v^{max}} = \frac{Ch_\theta(x)^{max}}{n^2/2 - 3n/2 + 1} \tag{B.13}$$

The index is between 0 and 1, representing a vulnerable system when v tends toward 1 and resilient otherwise. It assumes that a resilient system has a diffuse presence of shortest paths all over the grid while a dense concentration through a small number of spatial elements determines a vulnerability condition.

The Evacuation route index - ERI (**ID 19**) [23] evaluates the number of evacuation routes. This evaluates the provision of secure evacuation routes in urban areas, calculated with the Equation B.14.

$$ERI = \left(\frac{\sum n.\ Evacuation\ Ruote}{\left(inhabitants/100 \right)} \right) [\mathrm{n} / \mathrm{inh}] \tag{B.14}$$

Reasoning in these terms, it is necessary to think about the entire evacuation system so that it is as fast as possible.

Similarly to the Cr (ID **15**), the Congestion degree in crowded areas (**ID 20**) [65] estimates the crowding condition in crowded areas and is calculated with the Equation B.15.

$$C_A = \sum \left[\frac{people\ in\ crowded\ area}{(evacuation\ sites \times number\ of\ paths)} \right] \tag{B.15}$$

The Connectivity index - c (**ID 21**) [63] is defined as the relationship between the street links - S_{link} and the street nodes - S_{node}.

$$c = s_{link} / s_{node} \tag{B.16}$$

In particular, S_{link} represents the number of street links connecting street nodes (e.g. crossroads and decision points along the paths), while S_{node} represents the number of street nodes. The presence of nodes along the street links allows a faster and safer evacuation as they provide users with the opportunity to choose the best route and avoid roads blocked by debris.

The Evacuation time percentile - TN_{95} (**ID 22**) [72] has been elected as a KPI (K7 in Table 2) and has already discussed in section 3.1.

The Crowd effects - PN (**ID 23**) and the Number of deaths/casualties - CR (**ID 24**) are fundamental aspects in the design of evacuation plans [33,69]. The first parameter considers the negative effects that can occur during an evacuation (e.g., the risk of falling, limited physical capabilities etc.), compounded by the increased number of people trying to leave a building within a short period of time. The second PI is a promising method for implementing more rational and quantitative estimates of earthquake fatalities. The estimate of the victims considers the evacuation time as the main variable, since it depends on the parameters of the BE (number of exits, obstacles, etc.) and the physical characteristics of the users (fragility, age, etc.). Either PIs are elected as KPI (respectively K8 and K11 in Table 2) and are made directly from the behavioural-based simulation model.

The Proximity index - PI (**ID 26**) [23] lend themselves to this purpose in that they emphasize the importance of the pedestrian staircase and evaluates the distribution of urban services (schools, health centres, sports facilities, etc.) as a function of the citizens who benefit from it. This factor is calculated with the Equation B.17.

$$PI = \left(inhabitants\ near\ basic\ services/_{tot.\ inhabitants} \right) \times 100\ [\%] \tag{B.17}$$

The Occupancy Index for the link - O_{link} (**ID 27**) [15] represents the debris area along the link in question and is calculated with the Equation B.18.

$$O_{link} = min\left(\frac{A_{debris,link} + N_{av,link} \times \left(1 + \%\sigma_{N_{av,link}}\right) \times dA_{ped,D}}{W_{link} \times L_{link}}; 1 \right) \tag{B.18}$$

where $A_{debris,\ link}$ [m^2] is the area of debris along the considered link, $N_{av,link}$ is the number of evacuees using a certain *link* to reach a certain CSA, is $dA_{ped,D}$ [m^2] the average moving pedestrian's area (fixed at 0.25 m^2) in Level of Service D conditions, W_{link} is the width of the link and L_{link} is the length of the link (both expressed in [m].

This parameter is used to consider interference from debris and associated slowdowns in CSA pathway. Safety Index for rescuers' access route - $S_{link,SAA}$ (**ID 28**) [15] is the number of connections that make up the first aid attendant pathway. The index considers all the number of links that composes the rescuers' access path.

$$S_{link,SAA} = \left(\frac{A_{debris,link}}{A_{eff,link} / dA_{ped,D}} \right) \times \left(min\left(\frac{N_{av,link}}{A_{eff,link} / dA_{ped,D}}; 1 \right) \right) \times \left(1 - \frac{pos_{link}}{n_{link,route}} \right) \tag{B.19}$$

where pos_{link} is the position of the considered link inside the rescuers' path can be evaluated by considering the number $n_{link,\ route}$ of links composing the access route. The overall value is 1.0 for the link closer to the SAA.

Where possible, more than one route of access should be identified (at least two alternatives, given what is noted above for the CSA). The preferred approach should be the shortest with minimal interference conditions [15].

The number of evacuees - R_e (**ID 29**) [70] is based on the assessment of the percentage of people who can effectively participate in the evacuation compared to the total number of people involved in the event. Earthquake-related experience and education can prevent injuries and self-identification and self-help play key roles in emergency and medical rescue responses. The R_e has been integrated and improved with the Number of Evacuees for SUODs - R_{evac} (**ID 32**) [70], and elected as KPI (K10 in Table 2), since considers the ratio between all the people who can effectively succeed in the evacuation, and the original (pre-SUOD) number of exposed people. It is oriented towards earthquake evacuation since it considers effects of debris and terrorist act effects on the exposed inhabitants (those placed in indoor and outdoor who can be ideally sensible to the SUOD, at the starting time t0 of the event). This value varies from 0 (worst conditions, since all the people were not able to participate in the evacuation) and 100% (best conditions).

The mean flow rate at the exit - FN_{95} (**ID 30**) [71] has been elected as a KPI (K9 in Table 2) and has already discussed in section 3.1.

The Obstacle protection rate - O_p (ID 34) [62] is a new elaborated PI, valid for terrorist act only, since it considers the distance [m] between the user and a protective obstacle in respect to its distance [m] from the attackers. This PI is the last indicator elected as a KPI (K12 in Table 2) presented in Section 3.1.

References

[1] L.B.L. da Silva, J.S. Humberto, M.H. Alencar, R.J.P. Ferreira, A.T. de Almeida, GIS-based multidimensional decision model for enhancing flood risk prioritization in urban areas, Int. J. Disaster Risk Reduc. 48 (2020) 101582, https://doi.org/10.1016/j.ijdrr.2020.101582.

[2] M. Kalaycıoğlu, S. Kalaycıoğlu, K. Çelik, R. Christie, M.E. Filippi, An analysis of social vulnerability in a multi-hazard urban context for improving disaster risk reduction policies: the case of Sancaktepe, İstanbul, Int. J. Disaster Risk Reduc. 91 (2023) 103679, https://doi.org/10.1016/j.ijdrr.2023.103679.

[3] S. Bera, K. Gnyawali, K. Dahal, R. Melo, M. Li-Juan, B. Guru, G. V Ramana, Assessment of shelter location-allocation for multi-hazard emergency evacuation, Int. J. Disaster Risk Reduc. 84 (2023) 103435, https://doi.org/10.1016/j.ijdrr.2022.103435.

[4] L. Bernabei, G. Mochi, G. Bernardini, E. Quagliarini, Seismic risk of Open Spaces in Historic Built Environments: a matrix-based approach for emergency management and disaster response, Int. J. Disaster Risk Reduc. 65 (2021) 102552, https://doi.org/10.1016/j.ijdrr.2021.102552.

[5] T.L. Moe, P. Pathranarakul, An integrated approach to natural disaster management: public project management and its critical success factors, Disaster Prevention and Management, Int. J. (2006), https://doi.org/10.1108/09653560610669882.

[6] International Unisdr, Recovery Platform, European Commission, ReliefWeb, Book: Guidance Note on Recovery: Pre-disaster Recovery Planning, UN International Strategy for Disaster Reduction, International Recovery Platform, 2012.

[7] K. Rus, V. Kilar, D. Koren, Resilience assessment of complex urban systems to natural disasters: a new literature review, Int. J. Disaster Risk Reduc. 31 (2018) 311–330, https://doi.org/10.1016/j.ijdrr.2018.05.015.

[8] G. Bernardini, M. D'Orazio, E. Quagliarini, Towards a "behavioural design" approach for seismic risk reduction strategies of buildings and their environment, Saf. Sci. 86 (2016) 273–294, https://doi.org/10.1016/j.ssci.2016.03.010.

[9] B. Dong, D. Yan, Z. Li, Y. Jin, X. Feng, H. Fontenot, Modeling occupancy and behavior for better building design and operation—a critical review, Build. Simulat. 11 (2018) 899–921, https://doi.org/10.1007/s12273-018-0452-x.

[10] C.-A. Tai, Y.-L. Lee, C.-Y. Lin, Urban disaster prevention shelter location and evacuation behavior analysis, J. Asian Architect. Build Eng. 9 (2010) 215–220, https://doi.org/10.3130/jaabe.9.215.

[11] R. Robat Mili, K. Amini Hosseini, Y.O. Izadkhah, Developing a holistic model for earthquake risk assessment and disaster management interventions in urban fabrics, Int. J. Disaster Risk Reduc. 27 (2018) 355–365, https://doi.org/10.1016/j.ijdrr.2017.10.022.

[12] A. Pacheco Barzallo, J. Fariña, E. Álvarez de Andrés, Public open spaces: enabling or Impeding inclusive evacuation during disasters, The Journal of Public Space 7 (2022) 79–92, https://doi.org/10.32891/jps.v7i2.1474.

[13] G.P. Cimellaro, F. Ozzello, A. Vallero, S. Mahin, B. Shao, Simulating earthquake evacuation using human behavior models, Earthq. Eng. Struct. Dynam. 46 (2017) 985–1002, https://doi.org/10.1002/eqe.2840.

[14] K. Øien, I.B. Utne, R.K. Tinmannsvik, S. Massaiu, Building Safety indicators: Part 2 – application, practices and results, Saf. Sci. 49 (2011) 162–171, https://doi.org/10.1016/j.ssci.2010.05.015.

[15] A. Zlateski, M. Lucesoli, G. Bernardini, T.M. Ferreira, Integrating human behaviour and building vulnerability for the assessment and mitigation of seismic risk in historic centres: Proposal of a holistic human-centred simulation-based approach, Int. J. Disaster Risk Reduc. 43 (2020) 101392, https://doi.org/10.1016/j.ijdrr.2019.101392.

[16] R. Zhu, J. Lin, B. Becerik-Gerber, N. Li, Human-building-emergency interactions and their impact on emergency response performance: a review of the state of the art, Saf. Sci. 127 (2020) 104691, https://doi.org/10.1016/j.ssci.2020.104691.

[17] J. Lin, R. Zhu, N. Li, B. Becerik-Gerber, How occupants respond to building emergencies: a systematic review of behavioral characteristics and behavioral theories, Saf. Sci. 122 (2020) 104540, https://doi.org/10.1016/j.ssci.2019.104540.

[18] J. Han, Q. Wu, L. Zhang, C. Lei, How can the urban emergency capability gap be measured? Construction of a standardized indicator system in China, Int. J. Disaster Risk Reduc. 80 (2022) 103236, https://doi.org/10.1016/j.ijdrr.2022.103236.

[19] A. Thakur, R. Beck, S. Mostaghim, D. Grosmann, Survey into predictive key performance indicator analysis from data mining perspective, in: 2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA, IEEE, 2020, pp. 476–483, https://doi.org/10.1109/ETFA46521.2020.9212111.

[20] A.M. El-Maissi, S.A. Argyroudis, M.M. Kassem, F.M. Nazri, Integrated seismic vulnerability assessment of road network in complex built environment toward more resilient cities, Sustain. Cities Soc. 89 (2023) 104363, https://doi.org/10.1016/J.SCS.2022.104363.

[21] F. Giuliani, A. De Falco, V. Cutini, Rethinking earthquake-related vulnerabilities of historic centres in Italy: insights from the Tuscan area, J. Cult. Herit. 54 (2022) 79–93, https://doi.org/10.1016/j.culher.2022.01.004.

[22] C. Zhai, Y. Zhao, W.P. Wen, H. Qin, L.L. Xie, A novel urban seismic resilience assessment method considering the weighting of post-earthquake loss and recovery time, Int. J. Disaster Risk Reduc. 84 (2023) 103453, https://doi.org/10.1016/J.IJDRR.2022.103453.

[23] I. Tumini, P. Villagra-Islas, G. Herrmann-Lunecke, Evaluating reconstruction effects on urban resilience: a comparison between two Chilean tsunami-prone cities, Nat. Hazards 85 (2017) 1363–1392, https://doi.org/10.1007/s11069-016-2630-4.

[24] J. León, A. March, Urban morphology as a tool for supporting tsunami rapid resilience: a case study of Talcahuano, Chile, Habitat Int. 43 (2014) 250–262, https://doi.org/10.1016/j.habitatint.2014.04.006.

[25] G. Álvarez, M. Quiroz, J. León, R. Cienfuegos, Identification and classification of urban micro-vulnerabilities in tsunami evacuation routes for the city of Iquique, Chile, Natural Hazards and Earth System Sciences Discussions (2018) 1–20, https://doi.org/10.5194/nhess-2017-458.

[26] M. Morganti, Spatial metrics to investigate the impact of urban form on Microclimate and building energy performance: an essential overview, in: M. Palme, A. Salvati (Eds.), Urban Microclimate Modelling for Comfort and Energy Studies, Springer, Cham, 2021, pp. 385–402, https://doi.org/10.1007/978-3-030-65421-4_18.

[27] M. Dolce, A. Prota, B. Borzi, F. da Porto, S. Lagomarsino, G. Magenes, C. Moroni, A. Penna, M. Polese, E. Speranza, G.M. Verderame, G. Zuccaro, Seismic risk assessment of residential buildings in Italy, Bull. Earthq. Eng. 19 (2021) 2999–3032, https://doi.org/10.1007/s10518-020-01009-5.

[28] E. Mignot, X. Li, B. Dewals, Experimental modelling of urban flooding: a review, J. Hydrol. 568 (2019) 334–342, https://doi.org/10.1016/j.jhydrol.2018.11.001.

[29] G. Bernardini, G. Romano, L. Soldini, E. Quagliarini, How urban layout and pedestrian evacuation behaviours can influence flood risk assessment in riverine historic built environments, Sustain. Cities Soc. 70 (2021) 102876, https://doi.org/10.1016/j.scs.2021.102876.

[30] J.D.B. Cadena, G. Salvalai, G. Bernardini, E. Quagliarini, Determining behavioural-based risk to SLODs of urban public open spaces: key performance indicators definition and application on established built environment typological scenarios, Sustain. Cities Soc. (2023) 104580, https://doi.org/10.1016/j.scs.2023.104580.

[31] A. D'Amico, M. Russo, M. Angelosanti, G. Bernardini, D. Vicari, E. Quagliarini, E. Currà, Built environment typologies prone to risk: a cluster analysis of open spaces in Italian cities, Sustainability 13 (2021) 9457, https://doi.org/10.3390/su13169457.

[32] E. Quagliarini, F. Fatiguso, M. Lucesoli, G. Bernardini, E. Cantatore, Risk reduction strategies against terrorist acts in urban built environments: towards sustainable and human-centred challenges, Sustainability 13 (2021) 901, https://doi.org/10.3390/su13020901.

[33] X. Du, Y. Chen, A. Bouferguene, M. Al-Hussein, An agent-based simulation framework for analysing fall risk among older adults in the evacuation procedures, Saf. Sci. 129 (2020) 104790, https://doi.org/10.1016/j.ssci.2020.104790.

[34] N. Zhang, H. Huang, B. Su, J. Zhao, Analysis of dynamic road risk for pedestrian evacuation, Phys. Stat. Mech. Appl. 430 (2015) 171–183, https://doi.org/10.1016/j.physa.2015.02.082.

[35] E. Quagliarini, G. Bernardini, M. D'Orazio, How could increasing Temperature scenarios alter the risk of terrorist acts in different historical squares? A simulation-based approach in typological Italian squares, Heritage 6 (2023) 5151–5188, https://doi.org/10.3390/heritage6070274.

[36] E. Quagliarini, G. Bernardini, G. Romano, M. D'Orazio, Users' vulnerability and exposure in Public Open Spaces (squares): a novel way for accounting them in multi-risk scenarios, Cities 133 (2023) 104160, https://doi.org/10.1016/j.cities.2022.104160.

[37] M. Angelosanti, L. Bernabei, M. Russo, A. D'Amico, E. Cantatore, G. Bernardini, F. Fatiguso, G. Salvalai, G. Mochi, E. Quagliarini, E. Currà, Towards a multi-risk assessment of open spaces and its users: a rapid survey form to collect and manage risk factors, in: J.R. Littlewood, R.J. Howlett, L.C. Jain (Eds.), Sustainability in Energy and Buildings. Proceedings of SEB 2021 (Series Title: Smart Innovation, Systems and Technologies - Series ISSN: 2190-3018), Springer Singapore, 2022, pp. 209–218, https://doi.org/10.1007/978-981-16-6269-0_18.

[38] S. Han, Y. Ye, Y. Song, S. Yan, F. Shi, Y. Zhang, X. Liu, H. Du, D. Song, A systematic review of objective factors influencing behavior in public open spaces, Front. Public Health 10 (2022), https://doi.org/10.3389/fpubh.2022.898136.

[39] F. Rosso, L. Bernabei, G. Bernardini, M. Russo, M. Angelosanti, E. Currà, E. Quagliarini, G. Mochi, Urban morphology parameters towards multi-risk scenarios for squares in the historical centers: analyses and definition of square typologies and application to the Italian context, J. Cult. Herit. 56 (2022) 167–182, https://doi.org/10.1016/j.culher.2022.06.012.

[40] The European Commission, Security by Design: Protection of Public Spaces from Terrorist Attacks, 2022, https://doi.org/10.2760/924520.

[41] Z. Kalvach, et al., Basics of Soft Targets Protection - Guidelines (2nd Version), Prague, 2016. https://www.mvcr.cz/cthh/soubor/basics-of-soft-target-protection-guidelines.aspx.

[42] G. Zuccaro, M. Dolce, D. De Gregorio, E. Speranza, C. Moroni, La Scheda Cartis Per La Caratterizzazione Tipologico- Strutturale Dei Comparti Urbani Costituiti Da Edifici Ordinari. Valutazione dell'esposizione in analisi di rischio sismico, GNGTS 2016 (2015) 281–287.

[43] F.T. da Silva, N.C. Reis, J.M. Santos, E.V. Goulart, C.E. de Alvarez, Influence of urban form on air quality: the combined effect of block typology and urban planning indices on city breathability, Sci. Total Environ. 814 (2022) 152670, https://doi.org/10.1016/j.scitotenv.2021.152670.

[44] G. Bernardini, T.M. Ferreira, Emergency and evacuation management strategies in earthquakes: towards holistic and user-centered methodologies for their design and evaluation, in: T.M. Ferreira, H. Rodrigues (Eds.), Seismic Vulnerability Assessment of Civil Engineering Structures at Multiple Scales, Woodhead Publishing - Elsevier, 2022, pp. 275–321, https://doi.org/10.1016/B978-0-12-824071-7.00002-0.

[45] G. Bernardini, E. Quagliarini, M. D'Orazio, Towards creating a combined database for earthquake pedestrians' evacuation models, Saf. Sci. 82 (2016) 77–94, https://doi.org/10.1016/j.ssci.2015.09.001.

[46] G. Bernardini, E. Quagliarini, Terrorist acts and pedestrians' behaviours: first insights on European contexts for evacuation modelling, Saf. Sci. 143 (2021) 105405, https://doi.org/10.1016/j.ssci.2021.105405.

[47] C. Curt, Multirisk: what trends in recent works? – a bibliometric analysis, Sci. Total Environ. 763 (2021) 142951, https://doi.org/10.1016/j.scitotenv.2020.142951.

[48] E. Currà, A. D'Amico, M. Russo, M. Angelosanti, C.D.L. Cui, E. Quagliarini, H-Bet Historic Built Environment Typologies. Open spaces and SUOD events in the compact historic town, VITRUVIO - International Journal of Architectural Technology and Sustainability (2023), https://doi.org/10.4995/vitruvio-ijats.2023.18822.

[49] G.T. Doran, There's a SMART. Way to write managements's goals and objectives, Manag. Rev. 70 (11) (1981) 35–36.

[50] M. Russo, M. Angelosanti, G. Bernardini, L. Severi, E. Quagliarini, E. Currà, Factors influencing the intrinsic seismic risk of open spaces in existing built environments: a systematic review, Sustainability 14 (2022) 42, https://doi.org/10.3390/su14010042.

[51] E. Cantatore, E. Quagliarini, F. Fatiguso, European cities prone to terrorist threats: phenomenological analysis of historical events towards risk matrices and an early parameterization of urban built environment outdoor areas, Sustainability 14 (2022) 12301, https://doi.org/10.3390/su141912301.
[52] G. Salvalai, E. Quagliarini, J.D. Blanco Cadena, Built environment and human behavior boosting Slow-onset disaster risk, in: R. Amoeda, S. Lira, C. Pinhiero (Eds.), Heritage 2020 - Proceedings of the 7th Internationl Conference on Heritage and Sustainable Development, Green Lines Institute for Sustainable Development, 2020, pp. 199–209.
[53] International Organization for Standardization, Automation Systems and Integration — Key Performance Indicators (KPIs) for Manufacturing Operations Management — Part 2: Definitions and Descriptions, 2014. ISO 22400-2:2014 -.
[54] International Organization for Standardization, ISO 14031:2021 - Environmental Management — Environmental Performance Evaluation — Guidelines, 2021.
[55] International Organization for Standardization, ISO 13053-1:2011 - Quantitative Methods in Process Improvement — Six Sigma — Part 1: DMAIC Methodology, 2011.
[56] BE S2ECURE Project D 4.1.1 | Selected SLOD/SUOD Simulation Tool for BETs Delivered, 2022.
[57] F. Hissel, G. Morel, G. Pescaroli, H. Graaff, D. Felts, L. Pietrantoni, Early warning and mass evacuation in coastal cities, Coastal Engineering 87 (2014) 193–204, https://doi.org/10.1016/j.coastaleng.2013.11.015.
[58] G. Bernardini, T.M. Ferreira, Simulating to evaluate, manage and improve earthquake resilience in historical city centers: application to an emergency simulation-based method to the historic centre of Coimbra, ISPRS - international Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences (2020) 651–657, https://doi.org/10.5194/isprs-archives-XLIV-M-1-2020-651-2020. XLIV-M-1–2.
[59] E. Ronchi, E.D. Kuligowski, P.A. Reneke, R.D. Peacock, D. Nilsson, The Process of Verification and Validation of Building Fire Evacuation Models, NIST Technical Note, 2013, p. 1822.
[60] C.N. van der Wal, D. Formolo, M.A. Robinson, S. Gwynne, Examining evacuee response to emergency communications with agent-based simulations, Sustainability 13 (2021) 4623, https://doi.org/10.3390/su13094623.
[61] G. Bernardini, E. Quagliarini, M. D'Orazio, Toward quick multi-risk mitigation in historic Public Open Spaces: a behavioral-design approach in typological scenarios for heatwaves and terrorist acts, in: Extended Abstracts of the Xth Edition of the ReUSO - Documentation, Restoration and Reuse of Heritage, 2022, pp. 223–224.
[62] R. Zhu, G.M. Lucas, B. Becerik-Gerber, E.G. Southers, Building preparedness in response to active shooter incidents: results of focus group interviews, Int. J. Disaster Risk Reduc. 48 (2020) 101617, https://doi.org/10.1016/j.ijdrr.2020.101617.
[63] J. León, C. Mokrani, P. Catalán, R. Cienfuegos, C. Femenías, The role of built environment's physical urban form in supporting rapid tsunami evacuations: using computer-based models and real-world data as examination tools, Frontiers in Built Environment 4 (2019), https://doi.org/10.3389/fbuil.2018.00089.
[64] Z. Wang, G. Jia, A novel agent-based model for tsunami evacuation simulation and risk assessment, Nat. Hazards 105 (2021) 2045–2071, https://doi.org/10.1007/s11069-020-04389-8.
[65] M. Kanno, Y. Ehara, M. Hirota, S. Yokoyama, H. Ishikawa, Visualizing high-risk paths using Geo-tagged social data for disaster mitigation, in: Proceedings of the 9th ACM SIGSPATIAL Workshop on Location-Based Social Networks, ACM, New York, NY, USA, 2016, pp. 1–8, https://doi.org/10.1145/3021304.3021308.
[66] R. Der Sarkissian, C. Abdallah, J.M. Zaninetti, S. Najem, Modelling intra-dependencies to assess road network resilience to natural hazards, Nat. Hazards 103 (2020) 121–137, https://doi.org/10.1007/s11069-020-03962-5.
[67] F. Giuliani, A. De Falco, V. Cutini, The role of urban configuration during disasters. A scenario-based methodology for the post-earthquake emergency management of Italian historic centres, Saf. Sci. 127 (2020) 104700, https://doi.org/10.1016/j.ssci.2020.104700.
[68] M. D'Orazio, S. Longhi, P. Olivetti, G. Bernardini, Design and experimental evaluation of an interactive system for pre-movement time reduction in case of fire, Autom. ConStruct. 52 (2015) 16–28, https://doi.org/10.1016/j.autcon.2015.02.015.
[69] S. Li, C. Zhai, L. Xie, Occupant evacuation and casualty estimation in a building under earthquake using cellular automata, Phys. Stat. Mech. Appl. 424 (2015) 152–167, https://doi.org/10.1016/j.physa.2015.01.008.
[70] P. Kang, Y. Lv, Q. Deng, Y. Liu, Y. Zhang, X. Liu, L. Zhang, Investigating Lushan earthquake victims' individual behavior response and rescue Organization, Int. J. Environ. Res. Publ. Health 14 (2017) 1556, https://doi.org/10.3390/ijerph14121556.
[71] C. Feliciani, I. Zuriguel, A. Garcimartín, D. Maza, K. Nishinari, Systematic experimental investigation of the obstacle effect during non-competitive and extremely competitive evacuations, Sci. Rep. 10 (2020) 15947, https://doi.org/10.1038/s41598-020-72733-w.
[72] G. Bernardini, F. Finizio, M. Postacchini, E. Quagliarini, Assessing the flood risk to evacuees in outdoor built environments and relative risk reduction strategies, Int. J. Disaster Risk Reduc. 64 (2021) 102493, https://doi.org/10.1016/j.ijdrr.2021.102493.
[73] D.D. Aman, G. Aytac, Multi-criteria decision making for city-scale infrastructure of post-earthquake assembly areas: case study of Istanbul, Int. J. Disaster Risk Reduc. 67 (2022) 102668, https://doi.org/10.1016/j.ijdrr.2021.102668.
[74] L.D. Vanumu, K. Ramachandra Rao, G. Tiwari, Fundamental diagrams of pedestrian flow characteristics: a review, European Transport Research Review 9 (2017) 49, https://doi.org/10.1007/s12544-017-0264-6.
[75] G. Bernardini, E. Quagliarini, M. D'Orazio, Investigating exposure in historical scenarios: how people behave in fires, earthquakes and floods, in: A. Aguilar, R. Torrealva, D. Moreira, S. Pando, M.A. Ramos (Eds.), Structural Analysis of Historical Constructions - RILEM Bookseries, first ed., Cham, 2019, pp. 1138–1151, https://doi.org/10.1007/978-3-319-99441-3_123.
[76] P. Lu, M. Li, Z. Zhang, The crowd dynamics under terrorist attacks revealed by simulations of three-dimensional agents, Artif. Intell. Rev. (2023), https://doi.org/10.1007/s10462-023-10452-0.
[77] U. Wilensky, W. Rand, An Introduction to Agent-Based Modeling. Modeling Natural, Social, and Engineered Complex Systems with NetLogo, MIT Press., 2015.
[78] R. Liu, D. Jiang, L. Shi, Agent-based simulation of alternative classroom evacuation scenarios, Frontiers of Architectural Research 5 (2016) 111–125, https://doi.org/10.1016/j.foar.2015.12.002.
[79] R. Zhao, C. Fang, J. Liu, L. Zhang, The evaluation and obstacle analysis of urban resilience from the multidimensional perspective in Chinese cities, Sustain. Cities Soc. 86 (2022) 104160, https://doi.org/10.1016/j.scs.2022.104160.
[80] E. Bosina, U. Weidmann, Estimating pedestrian speed using aggregated literature data, Phys. Stat. Mech. Appl. 468 (2017) 1–29, https://doi.org/10.1016/j.physa.2016.09.044.