Sustainable Cities and Society 127 (2025) 106412

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

From single to multi-risk perspective: How heatwaves risk mitigation solutions can reduce terrorist risk in historic outdoor open areas

Gabriele Bernardini [a], Gessica Sparvoli [a], Elena Cantatore [b,*], Silvana Bruno [b], Fabio Fatiguso [b], Ilaria Isacco [c], Graziano Salvalai [c], Enrico Quagliarini [a]

[a] Department of Construction, Civil Engineering and Architecture, Università Politecnica delle Marche, Ancona, Italy
[b] Department of Civil, Environmental, Land, Construction and Chemistry, Politecnico di Bari, Bari, Italy
[c] Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Via Giuseppe Ponzio 31, 20133 Milan, Italy

ARTICLE INFO

Keywords:
Multi-risk assessment
Risk mitigation
Historic outdoor open areas
Users' behaviours in disasters
Simulation-based assessment
Heatwaves
Terrorist acts

ABSTRACT

Historical outdoor Open Areas (hOA) are relevant "hot-spots" in urban built environments, attracting many users due to morphological and use-related features. Besides significant heritage vulnerability, hOAs can also be affected by critical levels of users' exposure and vulnerability, exacerbating the effects of natural and anthropogenic risks. Mitigation solutions for one risk may impact others due to mutual interactions among different phenomena, necessitating multi-risk evaluations. This work focuses on how heatwaves-mitigation solutions ("slowly" impacting how users behave and gather in hOAs) can support risk-reduction for terrorist acts ("suddenly" striking users and implying evacuation) emerging in heatwaves-affected scenarios and, thus, multi-risk mitigation. To this end, an innovative approach for hOAs multi-risk analysis methodology is applied to a relevant case study (Piazza dell'Odegitria, Bari, Italy), using previously validated behavioural-based simulators. Original and post-retrofit (involving sustainable/highly reversible/compatible strategies with historical and cultural relevance of the place) scenarios are compared through multi-risk metrics, by analysing effects on hosted users. Results suggest remarkable and effective multi-risk reduction (>15 %) by combining, at least, cool pavement and barriers implemented with green elements. Moreover, the findings highlight the approach's capability to support policymakers in sustainably evaluating and comparing different scenarios for preliminary analyses of mitigation strategies.

1. Introduction

Historical outdoor Open Areas (hOAs), such as squares and streets, constitute critical "hot-spots" in the urban built environment for several issues, including those related to resilience of cities (Castaño-Rosa et al., 2022; Sharifi, 2019; Dastjerdi & Lak, 2023). In fact, they are characterised by relevant combinations of risk factors, in both natural and anthropogenic disasters, considering, on one hand, physical vulnerability and heritage features (including cultural and architectural value of the built environment), and, on the other hand, the effects of significant users' exposure and vulnerability (associated with the attractive role in respect of the surrounding urban fabric) (Han et al., 2022; Quagliarini et al., 2023a; Carmona, 2021). Therefore, decision-making activities aimed at promoting compatible and sustainable risk mitigation strategies should face complex scenarios (Castaño-Rosa et al., 2022; Sharifi, 2019; Dastjerdi & Lak, 2023; Li et al., 2023; French et al., 2019; Quesada-Ganuza et al., 2023). In addition, different risks can affect the hOA, in a single and compound manner, implying the adoption of single and multi-risk assessment and processes, and requiring advanced methods for the analysis of mitigation strategies effectiveness (Curt, 2021; Julià & Ferreira, 2021). To address these challenges, single and multi-risk conditions in hOAs should be characterised while also incorporating user-related factors (Section 1.1). Then advanced methods to move from single risk assessment to the multi-risk perspective should be adopted (Section 1.2).

1.1. Historical outdoor open areas (hOAs) as relevant scenarios in single and multi-risks perspectives

hOAs are part of urban built environments which can directly suffer natural disasters as a consequence of their presence in vulnerable areas, coherently with the scale of the phenomenon (e.g. flooding or seismic-

* Corresponding author.
E-mail address: elena.cantatore@poliba.it (E. Cantatore).

https://doi.org/10.1016/j.scs.2025.106412
Received 29 November 2024; Received in revised form 26 April 2025; Accepted 27 April 2025
Available online 1 May 2025

prone areas) (Castaño-Rosa et al., 2022; Galderisi & Limongi, 2021). Moreover, within the urban fabric, hOAs and, in particular squares, serve as social attractors and offer inherent opportunities in hosting mass-gathering events (Han et al., 2022; Quagliarini et al., 2023a). Therefore, they are usually featured by a high crowding level determined by the touristic appeal of sights and Special Buildings (e.g., churches, theatres), combining a significant presence of citizens/residents and tourists/visitors. This feature determines a double level of consecutive effects in hOAs (Cantatore et al., 2024; Cantatore et al., 2022). The first one relates to the increasing exposure levels of places that should be considered in risk assessment procedures for all possible disasters, and the second one concerns the higher proneness of such places in being soft targets of terrorist actions. In fact, considering the theories of risk disaster assessment [(Intergovernmental Panel on Climate Change (IPCC) 2023; UNDRR, 2016)], the crowd level influences the exposure-related dimension for suffered damage by people involved during natural hazardous events. In the case of terrorism, the crowd level, combined with the presence of symbolic or cultural buildings also increases the proneness of such public places to suffer from such violent acts (Cantatore et al., 2022; The European Commission, 2022; Federal Emergency Management Agency, 2007; Coaffee et al., 2009; Booth et al., 2020). For these reasons, from a user-centred point of view, the terroristic threat appears a challenging issue in urban policymakers' emergency management and prevention activities (Grissom et al., 2019; Desai, 2017). This perspective should be linked to the physical conditions of hOAs, considering how risk assessment knowledge should include main relations among inherent vulnerabilities, damage processes and effects on users, as well aesthetic rules and methods for their specificities.

The exposure-related dimension of users crowding in squares needs to be combined with the possible variety of users' typologies (i.e., age, level of autonomy in hOA fruition and movement, gender) that affect the overall users' vulnerability dimension in such places (Cadena et al., 2023; Bosina & Weidmann, 2017). In those terms, these user-related factors hence influence the dynamics of the emergency conditions for all the so-called SUdden Onset Disasters – SUODs (UNDRR, 2016), and can often imply the activation of evacuation procedures for users placed outdoors (Quagliarini et al., 2023b; Li et al., 2017; Song et al., 2022; Cao et al., 2022). In such contexts, the morphological and physical vulnerabilities of hOAs could lead to additional complexities in users-built environment interactions during the evacuation, because of e.g. narrow and complex layout of exit paths from the hOA, as well as poor implementation level of risk reduction strategies (The European Commission, 2022; Coaffee et al., 2009; Quagliarini et al., 2023b).

At the same time, the users' vulnerability also influences suffering external stressors on health and local wellbeing correlated to SLow Onset Disasters – SLODs (UNDRR, 2016), especially in a climate change-affected overall context (Castaño-Rosa et al., 2022; Carmona, 2021; Quesada-Ganuza et al., 2023; Estacio et al., 2022). In particular, hOAs can be located in historical cities where Urban Heat Island (UHI) effects can be significant and can potentially intensify the macro-scale phenomena related to heatwaves also at the scale of the single open space, increasing the final magnitude on fragile users (Quesada-Ganuza et al., 2023; Estacio et al., 2022; Liang et al., 2021; Salvalai et al., 2022). On the one side, the geographical location of hOAs may influence the intensity and frequency of extreme events also in combination with climate change. On the other factors such as the orientation of streets and buildings, the height-to-width ratio of built spaces, material properties, and the presence or absence of vegetation and water bodies (e.g., fountains) play a crucial role in determining the local variation of temperatures in terms of UHI (Castaño-Rosa et al., 2022; Gherri et al., 2021).

Despite the co-occurrence of disaster events is related to the frequence of events, SUODs and SLODs may also appear at the same time due to their different time scales (Curt, 2021; UNDRR, 2016). In the given hOA context, UHI effects may characterise long periods of the years, in view of its correlation with SLODs, while exploiting their peak intensity during a few days. Thus, hOA users – including passersby, visitors and customers of outdoor activities – may adapt their behaviours coherently to such boundary conditions (Han et al., 2022; Cadena et al., 2023; Cheung & Jim, 2019). For instance, users can move towards the area with reduced heat stress to face critical heatwaves-induced conditions (S Han et al., 2022). On the other hand, when a SUOD occurs, safety and emergency procedures occur faster among users, aiming at leaving risky areas (Li et al., 2017; Song et al., 2022; Bakhshian & Martinez-Pastor, 2023). For instance, in case of a terrorist act, the evacuation process is highly affected by the way users gather before the attack and by the local crowding levels (Quagliarini et al., 2023b; Lu et al., 2020). Similarly, it is expected that solutions aimed at SLODs mitigation can alter the response to SUODs, possibly providing additional risk reduction against them and thus an overall effect on multi-risk levels (Rosso et al., 2023). For instance, the implementation of greeneries in an hOA could vary the effects of the heatwave on users health, as well as their distribution in outdoors, but, at the same time, could provide obstacles to the evacuation process and protection elements against attackers (Rosso et al., 2023).

1.2. Multi-risk assessment methods for the built environment

The overview of Section 1.1, highlights how multi-risk assessment is challenging for safe and secure built environment, comprising both the wider urban scale and the single hOA one. Previous works stressed the role of multidisciplinary themes and multi-timing occurrences to this end.

In the widest applications of multi-hazard risk and multi-risk cases in cities, the goals are associated with specific conditions in real urban case studies which became the central settings for possible scenarios to test different approaches (Hochrainer-Stigler et al., 2023; Poljanšek et al., 2017; The United Nations Office for Disaster Risk Reduction (UNISDR) 2017; Pescaroli & Alexander, 2017). Scenarios usually result from various scales of hazard mapping analysis, from territory to specific built environment sub-areas and components (districts, building) (Galderisi & Limongi, 2021; Cardone et al., 2024; Amarnath et al., 2021), highlighting two main dimensions of possible interactions among hazards: time of occurrence and vulnerability of the built environment system. Scenarios in multi-hazard conditions are usually set focusing on:

- time-dependency of multiple hazards, exploring the possible co-occurrence and/or the cascading effects in the analysed case study (Pizzorni et al., 2024; Sáenz de Tejada et al., 2024). In this case, scenarios are derived ex ante to specific geographical conditions prone to the selected disasters or they are analysed after a suffered multi-hazard scenario (ex post). In both cases, scenarios are assessed in static conditions of vulnerabilities, properly linked to the specificity of the case study (ex-ante) or to the moment of the suffered events (ex-post) (Gómez Zapata et al., 2023; Polese et al., 2024; Biondi et al., 2023; Pal et al., 2023).
- The multi-hazard proneness to specific case studies mainly declined to assess strategies (a) or damage (b) in different, independent and asynchronous perils. In the first case (a), the main core of the analyses is the multi-hazard risk assessment of case studies in different states of vulnerability, considering the current state of the case study (ex-ante) and possible enhanced ones (mitigation strategies applied – ex-post) in variated hazard conditions (Cantatore et al., 2023; Schlumberger et al., 2022; Yu et al., 2024); in the second case (b), as-built conditions are assessed to evaluate different levels of vulnerabilities declined to the selected hazard in order to compare the risk in terms of final physical damages (on the built environment or economic loss) (Mascheri et al., 2024; Arrighi et al., 2023).

In both cases, the applications rely on static or semi-static qualification of changing scenarios, which is mainly employed in the pre-emergency or reconstruction phases of risk management. Recent works were mainly oriented towards rapid multi-risk assessment models with application to the urban scale as a whole (or to the territorial scale), widely using coarse analysis that do not allow to provide significant insights at the hOA scale (Pizzorni et al., 2024; Jato-Espino et al., 2025; Chen et al., 2023; Laino et al., 2024; Bernal et al., 2017).

Furthermore, the presence of people in the urban built environment is recently recognised as relevant in the emergency phase, where scenarios suddenly change also in single risks (Li et al., 2017; Song et al., 2022; Cheliotis, 2020; Senanayake et al., 2024). Besides the quantification of exposure in terms of the number of people potentially involved in the threat and hazard, the user involvement in the risk assessment is usually referred to two main goals in literature and best practices: the study of early-warning systems and evacuation plans to manage correct evacuation processes (de Ruiter & van Loon, 2022) and the risk communication and preparedness which, however, involved people before the events. Recent theoretical framework on user-centred approaches to multi-risk underlines the role of "bidirectional interactions between people and the systems that serve them" (Ouyang et al., 2024). Nevertheless, in both the aforementioned cases, users' features and behaviours at the individual level appear not largely explored in multi-hazard risk conditions, especially while focusing on the hOA scale, considering the coupling of hazards, and advanced simulation tools including users' behaviours in emergency (Julià & Ferreira, 2021; Quagliarini et al., 2023b; Ouyang et al., 2024). Considering the main context of multi-risk conditions affecting hOA, defined in Section 1.1, it is worth noting that works to model user behaviours and single risk effects in heatwaves (Cadena et al., 2023; Estacio et al., 2022; Zhao et al., 2024) and terrorist acts (Li et al., 2017; Song et al., 2022; Cao et al., 2022) exist, but efforts to couple them and to model them in historical urban contexts seem to still limited (Quagliarini et al., 2023b).

In this sense, to the best of the authors' knowledge, the so called "SLOD-to-SUO" simulation approach developed within the BE S^{2}ECURe project (BE S2ECURe, 2024) seems to represent one of the most complete methods towards the coupled assessment of built environment conditions affected by SLODs and SUODs, including risk-related users' behaviour and dynamics at the hOA scale level (Quagliarini et al., 2023b). In detail, the workflow first considers that SLOD conditions can affect the way users behave and occupy the hOA (e.g. in case of heatwaves, preferring areas with lower outdoor temperature values, to mitigate heat stress and improve comfort levels) (Cadena et al., 2023; Cheung & Jim, 2019). Then, when the SUOD occurs, users can gather in specific areas and be exposed to the SUOD effects themselves because of their positions (e.g. in the case of terrorist acts, crowding levels are higher in the attack area) (Curt, 2021; Quagliarini et al., 2023b). The capabilities of such an approach have been tested in idealised scenarios, highlighting how different input scenarios related to users' response to SLODs can alter the level of safety in SUODs emergencies (e.g. variation of evacuation timing, flows, and damages suffered by evacuees) (Quagliarini et al., 2023b).

Finally, previous works also provide different outputs related to the multi-risk assessment and mitigation analysis. The quantification of disaster losses (including economic and social) seem to constitute the way for homogenising different types and classes of risk hazards (i.e. usually, sudden events that provoke physical damages in the built environment) (Chen et al., 2023; Bernal et al., 2017). Nevertheless, the assessment of strategies in multi-risk scenarios in literature is also supported by the use of performance-based risk indicators (KPIs), which are widely used in the context of user-centred built environment performance (Li et al., 2021). These KPIs should be balanced to consider all the user-built environment interactions affecting single and multi-risk levels, and thus rely on the analysis of effective users' response and needs against surrounding stressors, as well as on risk effects on users (e.g. user health for SLODs, evacuation process for SUODs) (French et al., 2019; S Han et al., 2022; Bakhshian & Martinez-Pastor, 2023; Rus et al., 2018). Previous works tried to codify groups of KPIS to this end, but efforts to combine and interconnect them into unique risk metrics seems to be still limited (Cadena et al., 2023; D'Amico et al., 2024; Tumini et al., 2017).

1.3. Work aims

The paper adopts the "SLOD-to-SUOD" risk-assessment approach, and it adapts them to evaluate the efficacy of mitigative strategies in possible multi-hazard risk scenarios through simulation tools incorporating users' behaviours and associated metrics. Specifically, the approach evaluates how SLOD-oriented mitigation solutions can provide risk-reduction for a SUOD emerging in SLOD-affected scenarios, thus promoting first steps towards a holistic standpoint to multi-risk mitigation.

The application relates to the contexts of hOAs, and specifically to a square, as relevant hOA from a typological perspective for the attraction of users and related hazard conditions. Selected risks for the case study are heatwaves (HW) for SLODs, terrorist acts (T) for SUODs, and their contemporary occurrence. In fact, as discussed in Section 1.1, the touristic attractiveness of historical cities, especially during the holidays period and thus also during the summer season, can be critically combined in hOAs with the possible presence of Special Buildings (e.g. museums, theatres, or other historic sites open to the public and often subject to crowding). These conditions are mainly common to public hOAs in the wide historic Italian and European contexts, along with the absence of specific mitigation strategies (Intergovernmental Panel on Climate Change (IPCC) 2023).

Validated behavioural simulation tools are organized into a heatwaves-to-terrorist act application and are then used to perform analysis in pre- and post-retrofit scenarios concerning a hOA case study (Cadena et al., 2023; Quagliarini et al., 2023b). While pre-retrofit scenarios are based on the current hOA modelling, post-retrofit scenarios rely on the proposal of mitigation strategies which can be applied in the hOA. They focus on interventions applied in public outdoor spaces, and oriented towards heatwave mitigation, but having also possible effects also on terrorist acts. Single and multi-risk metrics are hence defined, combining literature-based performance indicators for SLODs and SUODs assessment (Cadena et al., 2023; D'Amico et al., 2024), according to the *Analytic Hierarchy Process* – AHP (Goepel, 2013).

The remainder of the paper is hence structured as follows. Section 2 traces the methodology in respect to the heatwaves-to-terrorist act application of the "SLOD-to-SUOD" approach, and it offers an overview of the selected representative case study, Piazza dell'Odegitria in Bari, Italy. Then, Section 3 provides the main methodology outputs, which comprises scenario creation, and single to multi-risk assessment results in pre- and post-retrofit scenarios. Finally, Section 4 offers the potentialities of the methodology based on the behavioural simulation-based approach and it tries to provide related insights for general risk-reduction strategies design in squares under the considered conditions.

2. Phases and methods

Fig. 1 outlines the risk assessment and mitigation framework, considering the general SLOD-to-SUOD approach (Quagliarini et al., 2023b) (top workflow) and its application to the HEATWAVES-to-TERRORIST ACTS application provided by this study (bottom workflow). This application accounts for the specificities of the considered case study (Piazza dell'Ogeditria, Bari, Italy), as outlined in Section 2.1. The framework is essentially organized in three main phases.

The first phase deals with the creation of scenarios to be assessed, using existing and validated methods which allow to model the physical conditions of the built environment, select the possible SLODs and SUODs affecting it, and quantify the users' vulnerability and exposure. In addition to the analysis of these elements in the pre-retrofit scenario, mitigation strategies, to face selected SLOD and SUOD by themselves

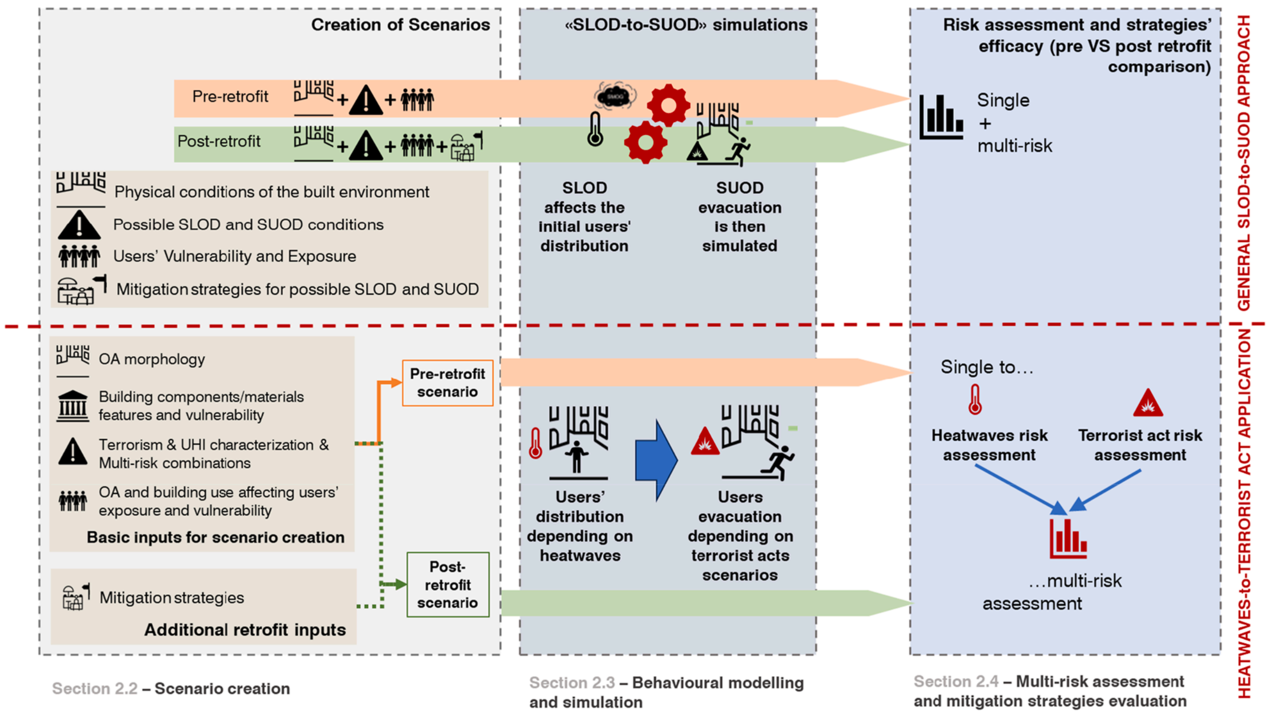

Fig. 1. Research framework and work phases, considering the general SLOD-to-SUOD approach (top workflow) and the specific application to heatwaves-to-terrorist acts analysed in the case study application. References to the methodological sections related to the heatwaves-to-terrorist acts application are also provided.

and in a combined manner, are also addressed, to define post-retrofit scenarios. Section 2.2 defines selected methods to the hOAs application in the context of heatwave (HW) and Terrorism (T) as relevant risks analysed in this work, also comprising general criteria and literature-based analysis for their effective applicability in hOAs.

The second phase concerns the simulation process, following a behavioural and "SLOD-to-SUOD" approach. This process employs previously validated simulation tools while considering the time scale of the analysed risks. The general approach considers that SLOD conditions are firstly assessed by simulating the effects of SLODs on the users, considering their behaviours in the fruition of the built environment. In particular, behavioural effects on users' distribution in outdoor spaces is mainly considered in view of: (1) the impact of critical levels in environmental parameters (e.g. temperature) requiring users' actions to restore adequate comfort levels (Cadena et al., 2023; Cheung & Jim, 2019); (2) the outcoming effects on crowding levels in outdoor areas, which can then impact SUODs conditions (Curt, 2021; Quagliarini et al., 2023b). Then, the SUOD-affected evacuation process is simulated, by modelling users' behaviours in evacuation conditions, depending on their mutual interaction in crowd movement, and on the interactions with the built environment and any external stressor (e.g. damage level, additional threats). In this simulation process, additional behavioural interactions towards SLOD and SUOD are also affected by implementing the selected mitigation strategies. In view of these general logics, Section 2.3 defines the specific SLOD-to-SUOD simulation model in the context of HW and T for the hOAs application.

Finally, the third phase regards the simulation-based multi-risk assessment of pre-retrofit scenarios and the subsequent evaluation of mitigation strategies' effectiveness in post-retrofit scenarios. In both cases, SLOD-to-SUOD simulation results are then organized into Key Performance Indicators (KPIs) to derive single risk metrics. In this way, the behavioural simulation-based approach determines the impact of (1) SLOD effects on the users (i.e. with respect to the users' health) (Cadena et al., 2023), and (2) the SUOD effects on the users, considering their initial SLOD-affected distribution in the built environment (i.e. with respect to the evacuation process analysis) (D'Amico et al., 2024). Then, single-risk metrics are combined into a unique multi-risk metric. Section 2.4 defines KPIs and metrics for single to multi-risk assessment in the contexts of HW and T for the hOAs application.

2.1. Case study application: Piazza dell'Odegitria, Bari, Italy

Piazza dell'Odegitria, located in Bari old town, Italy, has been chosen as the application case study for the heatwaves-to-terrorist act risk flow outlined in Fig. 1. This hOAs still maintains its ancient morphological configuration which is typical of many historical cities in the Mediterranean area, where rising temperatures and extreme heat events are becoming more frequent due to climate change. The square' morphology, the high density of the surrounding built environment, the use of local materials and techniques characterise the square as a typical Mediterranean one. Moreover, Piazza dell'Odegitria is one of the urban attractors for residents and tourists within the old town, merging the presence of residential, commercial, and religious activities, as well as the relevance of the urban sights. For these reasons, terrorist act risks (D'Amico et al., 2021) can be also evaluated.

In particular, from a morphological perspective, the square has a complex and convex shape, extending its surface for about 1300 m^2. Despite the plan shape complexity, Piazza dell'Odegitria is a compact square, with a ratio between width and length of about 0.72 (Gherri et al., 2021; D'Amico et al., 2021; De Lotto & Sturla, 2017) (Fig. 2). The average height of the surrounding buildings is 14.9 m, while the maximum one is 23.8 m and relates to the main church (i.e. the San Sabino Cathedral).

Concerning construction features and materials, Piazza dell'Odegitria partially maintains the original materiality of pavements, showing large and thick calcareous blocks (the so called "chiancarelle") along its boundary (Fig. 3). These elements were substituted with basalt stone blocks in the centre of the space, locally altering the albedo (α) value of the pavement. The calcareous material characterises the vertical surfaces, too. Non-plastered masonries are locally spaced out with plastered ones, although clear colours are widely present. Similar features can be recognised in roofing, where a calcareous pavement (thinner than the

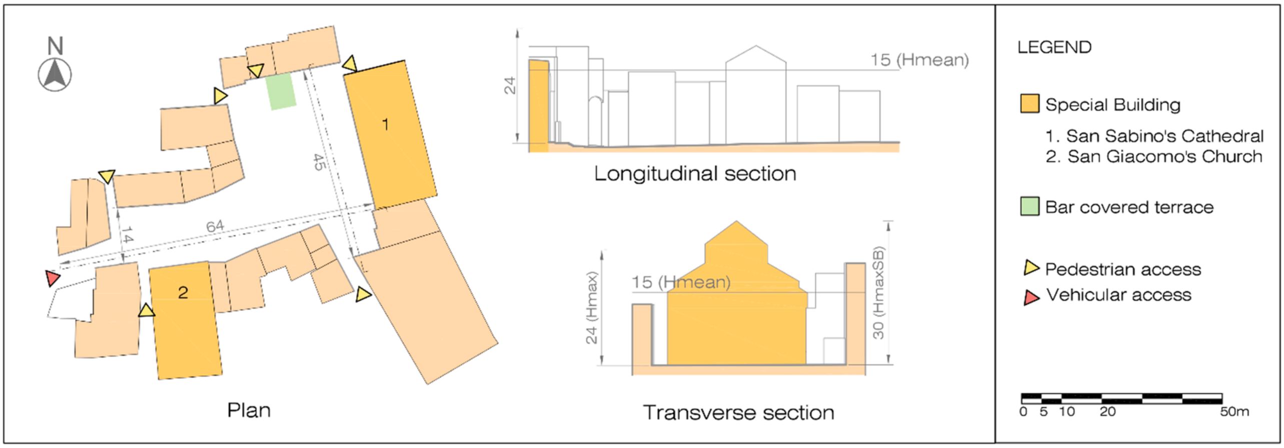

Fig. 2. Case study hOA layout and additional technical details of the main composing elements.

Fig. 3. View of Piazza dell'Odegitria, Bari, showing typical walls and pavement finishings representative of the Mediterranean urban context.

street one) can be seen (11 % extension). In addition, more recent materials were introduced, such as light-coloured bituminous surfaces and red tiles which characterise most of the roof extension (73 %). A limited extension of roof paving (18 %) is made of dark bituminous coats. Similar general features are shared by the surrounding urban fabric. The presence of light-coloured calcareous stone applied to vertical and horizontal built surfaces can provide benefits for the mitigation of local overheating in the context of the surrounding narrow streets entering the hOA, thus representing the inherent adaptability qualities of the Mediterranean historic places featured by hot summer; however, the morphological features of Piazza dell'Odegitria cannot exclude critical heatwaves effects (Cantatore & Fatiguso, 2021). In addition, increasing risk for Bari and, especially, for the old town has been recently reported by the Ministry of Health[1] and by recent studies about the Urban Heat Island intensity in the city (Sangiorgio et al., 2022). Therefore, in view of the above, Piazza dell'Odegitria can be considered a relevant hOA in the Mediterranean area prone to heatwaves risk.

Finally, concerning the intended uses of the hOA and of the surrounding buildings, Piazza dell'Odegitria hosts two special buildings, i. e. the San Sabino's Cathedral (a symbolic religious church for Apulian tourism) and the San Giacomo's Church (Fig. 2). Apart from the two churches, all the other buildings are used for commercial/warehouse activities on the ground floor (including a bar area in the outdoors organised by a fixed terrace) and for residential purposes on the upper storeys. The square is part of the old town pedestrian area, and vehicular access and transit are limited to inhabitants only (Fig. 2). Therefore, six pedestrian access streets to the square are present, while only the widest access street is accessible to vehicles. The presence of special buildings, the relevance of the square in the urban sights and thus the possibility to suffer from relevant crowding conditions, suggest that Piazza dell'Odegitria could be a significant public space and soft target in view of terrorist act risk (Cantatore et al., 2024; Cantatore et al., 2022).

[1] Ministero della Salute (2023) Piano nazionale per la prevenzione degli effetti del caldo sulla salute. https://www.salute.gov.it/portale/caldo/dettaglioContenutiCaldo.jsp?id=408&area=emergenzaCaldo&menu=vuoto (last access: 05/07/2024)

2.2. Scenarios creation for heatwaves-to-terrorist act assessment in hOAs

Methods used for the creation of pre-retrofit scenarios (Section 2.2.1) include the characterisation of basic morphological, hazard-related, and user-related inputs for simulations as shown in Fig. 1, while those relating to post-retrofit scenarios (Section 2.2.2) mainly focus on the criteria for selecting mitigation strategies in hOAs, considering the heatwaves-to-terrorist act risk context. These data are hence used as input for the simulation phase shown in Section 2.3.

2.2.1. Pre-retrofit scenarios definition

The definition of the pre-retrofit scenarios considers the original conditions of the physical environment, in terms of site orientation, morphology and layout. Therefore, buildings, special buildings, obstacles in the outdoors (including any greenery), each indoor and outdoor intended uses, and access streets are characterised in terms of typology and geometrical issues (plan and elevation).

Data on heatwave risk are collected and managed according to validated approaches (Cadena et al., 2023), and they include:

- Main features of the materials, in terms of both surface extension and position in the hOA (plan and elevation), as well as their albedo values.
- Local climate data analysis over the last 5 years to derive critical outdoor conditions for the hottest week of the year, during the time span from 11AM to 4PM.

Data about terrorist act risk rely on the analysis of the hOA as a soft target, thus including the identification of (Cantatore et al., 2024; Federal Emergency Management Agency, 2007; Kalvach, 2016; US department of Homeland Security, 2018; FEMA-426/BIPS-06, 2011):

- Attracting elements for perpetrators, such as special buildings and outdoor areas which can potentially imply significant (over)crowding levels.
- Structural and non-structural protection or mitigation measures related to terrorist act.
- Possible typologies and point of attack depending on frequentist assessment of terrorist acts, hOA morphology and previous issues on attracting elements and measures. In particular, previous research work pointed out the relevance of the two following typologies of attack for hOAs (Cantatore et al., 2024): armed assault with cold weapon, in which perpetrators attack the crowd with a sword or a knife (in the following, Attack Type 1 – AT1); the vehicle attack, in which perpetrators enter the hOA driving a vehicle to crash target (e.g., Special Building or bar covered terraces), running over the crowd placed along its trajectory (Attack Type 2 – AT2). Points of attack for AT1 and AT2, as well as the attack trajectory for AT2, should be proposed based on the position of the attracting elements and the presence of any obstacles, in order to primarily select scenarios that could ideally maximize the attack effects on hosted users, according to a conservative approach to terrorist act risk assessment. In addition, a baseline reference scenario AT0 is considered such as the simple evacuation from the hOA, thus with no attackers' effects on the users and no casualties (Quagliarini et al., 2023b).

Previous methods to determine exposure ("how many users are exposed?") and individual vulnerability ("which are the typologies of exposed users?") of users have been exploited to provide a time-dependent characterisation of these issues on a hourly scale, both in typical working days and typical holidays (i.e., Sundays and National Holidays) (Quagliarini et al., 2023a). The approach considers typologies of users, namely *tp*, who are generally placed outdoors according to hOA fruition rules, and thus can be directly exposed to the effects of heatwaves and terrorist acts in the hOA (Cadena et al., 2023; Quagliarini et al., 2023b). Each typology attends specific intended use in the hOAs and thus is placed in the related areas. Intended uses are rapidly associated with typical occupant load factor OL_i [persons/m^2], according to Fire Safety Standards and Codes. For the case study, Italian regulations have been considered (Ministry of Interior (Italy) 2020). In this work, considered *tp* are:

- Only Outdoor users (OO), such as passersby (including city visitors), occupy public walkable areas, including sidewalks, accessible green areas and parks. Their density is estimated at 0.1 persons/m^2 during peak hours, typically between 07:00 and 24:00, while it is assumed to be negligible (0.0 persons/m^2) between 01:00 and 06:00 due to reduced pedestrian activity.
- Prevalent Outdoor users (PO), such as customers of dehors of restaurants and bars, open markets and others outdoor areas related to specific buildings or intended uses, who generally spend time in the same area of the hOA for a more prolonged time than OO. Their density is estimated at 0.4 persons/m^2 during the opening time of the activities, while it is assumed to be 0.0 persons/m^2 when they are closed.
- Special Building users (SB) refers to the users of the hOA's Special Building. Following a conservative approach, they could gather in front of the Special Building waiting to enter, e.g., at the start or end of visits or religious services in the case of a church. Their density is estimated at 0.7 persons/m^2 during the special building opening times and 0.0 persons/m^2 when it is closed. The SB vulnerability is also related to the possibility to suffer from (over)crowding in the waiting area, thus affecting the hOA attractiveness to terrorist acts and the position of the point of attack.

In case of structured models, including BIM-based, are not available, each intended use *i* associated with *tp* can be identified by using Google Maps and Google Street View (www.google.it/maps/?hl=it; last access: 13/02/2025). For special buildings, these freeware tools can also be used to evaluate the number of storeys. The gross surface GS_i [m^2] of a given intended use *i* can be then estimated through rapid freeware online tools for plan surface measurement, such as combining Calcmaps (www.calcmaps.com/it/map-area; last access: 13/02/2025), excluding areas occupied by carriageways, parking lots, monuments, fountains, stairs, other fixed obstacles and fenced areas.

In view of the above, user exposure is quantified by the number of users (*NU*) [persons] in the hOA, which is hourly estimated through Eq. (1):

$$NU = \sum_{i,a} GS_i \cdot OL_i \tag{1}$$

Then, the density of users in the outdoor area D_{out} [persons/m^2] is hourly assessed dividing *NU* by gross outdoor area of the hOA. D_{out} can provide a rapid overview of exposure conditions for comparison purposes, supporting the identification of critical scenarios over the day and between working days and holidays.

Finally, individual vulnerability is described hourly in terms of the position ratio *PR* [%], which is calculated as the number of users by *tp* (or their sum) divided by the overall number of hosted users. *PR* hence ranges from 0 % (no users of a given *tp* are present) to 100 % (all the users are associated with the given *tp*). *PR* can also be provided by aggregating OO, PO and SB. In addition, the users' percentages by age is considered, to evaluate basic vulnerability differences in both health fragilities to heatwaves (Vanos et al., 2018; Bakhsh et al., 2018; Verstockt et al., 2011; Błażejczyk et al., 2014) and motion speeds in terrorist acts-related evacuation (Bosina & Weidmann, 2017; Quagliarini et al., 2023b; van der Wal et al., 2017). The age distribution of users can be obtained from freeware online census databases, e.g. ISTAT databases for Italy (https://demo.istat.it/?l=en; last access: 13/02/2025). This data source allows a rapid analysis of individual vulnerability but assumes homogeneous conditions in hOA use over time. Indeed, additional in-situ survey to detect typical users of public intended uses can provide additional details on the variation in age distribution hourly (Quagliarini et al., 2023a). Data are then aggregated according to the following age ranges: 0–4 years (toddlers, hand-assisted by parents); 5–14 years (children, assisted by parents); 15–19 years (young autonomous users); 20–69 years (adult users); 70+ years (autonomous elderly).

2.2.2. Post-retrofit scenarios definition

Post-retrofit scenarios consider basic inputs defined in Section 2.2.1 and apply selected mitigation strategies identified through the assessment of their potential impacts on the considered single risks. The same strategies are then evaluated from a multi-risk standpoint to define the best solutions to be implemented in the hOA. Therefore, the proposed approach for the identification of mitigation strategies follows three main standpoints (Julià & Ferreira, 2021; Rosso et al., 2023; Gandini et al., 2021):

1. Strategies are oriented towards the mitigation of heatwave, but they should also provide risk reduction in a terrorist act-affected scenario and, therefore, support risk reduction for a terrorist act emerging in heatwaves-affected scenarios.
2. Strategies essentially refer to possible interventions directly applicable by the local administration, being focused on the outdoor public spaces of the hOA.
3. Strategies are compatible with the overordered guidelines for the preservation of the cultural place and local codes. In particular, regulatory frameworks at city and territorial levels concerning structural interventions on building heritage and hOA should be considered depending on the effective application context.

To support the mitigation strategies selection, Table 1 resumes the macro-classes of strategies identified in previous literature review works (Rosso et al., 2023) for heatwaves (HW) and terrorist act (T), comprising their potential impact depending on hazard typology. In particular, as remarked in Table 1, each strategy has primarily potential impact on HW, and thus on the user distribution before a terrorist act. Some of them could also provide direct risk mitigation for T. It is worth highlighting that all the discussed strategies reflect a modification of the hOA current features, in both morphological, aesthetical, physical/constructive and risk performance standpoints.

The implementation in the hOA of “Trees” or “Mobile or fixed barriers combined with green elements” could have a very high potential impact on both HW and T. If applied in different parts of the hOA, these strategies could have a widespread effect on temperature reduction, as well as a direct consequence on users’ behaviours in the fruition of the hOA (e.g., during HW, users could prefer to gather in shadowed areas generated by the strategies implementation) and in their movement (being both obstacles inside the hOA). Moreover, they can be placed to reduce the effects of vehicle attacks (i.e., reducing vehicles speed) or even remove them (i.e., in case of effective obstacles along the ideal vehicle attack direction), or represent protective elements for users against attackers (especially for fixed barriers combined with green elements, such as engineered planters). “Seasonal shadings” could have a lower potential impact compared to these solutions. Although they can provide HW-mitigating shadowed areas (especially for PO users) and represent obstacles to the movement of users and attackers, their extent is mainly limited to some specific areas of the hOA due to technical installation issues. “Cool pavement", considered highly compatible with heritage preservation issues for the case study, is representative of possible high-impact solutions on the HW only. Finally, for each strategy selected for the application, depending on the compatibility with the hOA regulatory framework, a possible general implementation layout is proposed, displacing the related elements in the original physical built environment based on the hOA morphology. Then, albedo values are also collected and associated with surface extension using the same pre-retrofit scenario rules for HW modelling. Each post-retrofit scenario is then associated with the outcomes of this process. In addition, post-retrofit scenarios combining the selected strategies are also considered by essentially overlapping (or adapting, when needed) their implementation according to the general layout. In this way, the joint mitigation effectiveness can be assessed through the framework.

Table 1
Summary of morphological and physical/constructive strategies for the mitigation of heatwaves (HW) and terrorist act (T) risks in hOA, and their potential impact, according to previous classification approaches (Rosso et al., 2023).

Category	Strategy	Potential impact depending on hazard	
		HW	T
Morphological factors	**Trees**	high	medium
	Seasonal shadings	high	low
Physical and construction factors	**Cool pavement**	high	
	Mobile or fixed barriers combined with green elements	high	high
	Cool façade	high	
	Green walls	high	

2.3. Heatwaves-to-terrorist act behavioural modelling and simulation

The behavioural simulation has been performed according to the workflow shown in Fig. 4, using existing and agent-based models and tools developed in previous studies of the BE S^{2}ECURe project (Cadena et al., 2023; Quagliarini et al., 2023b).

The simulations are first focused on HW, using Rhinoceros V6 for the 3D modelling of the hOA according to the data from scenario creation (Section 2.2), combined with Ladybug tools 1.3.0 (including Honeybee), Grasshopper and ENVI-met v.5 for solar radiation and temperature calculation in outdoor spaces, and, thus, for the outdoor temperature evaluation, according to the Universal Thermal Climate Index (UTCI) [°C] (Cheung & Jim, 2019). The UTCI has been selected due to its effectiveness in providing reliable evaluations of outdoor thermal comfort despite requiring easily available input parameters (i.e., Dry Bulb Air Temperature, Mean Radiant Temperature, Relative Humidity, and Air/Wind Velocity), which can be extrapolated from EnergyPlus website .epw weather files. Unlike other indices, which often depend on extensive on-site data collection or computationally demanding simulations, adopting UTCI-based assessment eliminates the need for detailed field surveys, making it particularly suitable for applications in hOAs, where rapid and efficient modelling is essential (Park et al., 2014; Walls et al., 2015). Following approaches validated in previous studies (Cadena et al., 2023), the UTCI values have been calculated using the software ENVI-met and a UTCI Python code provided by Ladybug Tools. In detail, ENVI-met has been used to dynamically calculate the UTCI, while the Python code has been used to interpolate the UTCI results in the points where the ENVI-met modelling system discretises the case study geometry (i.e., where diagonal lines are translated into segmented ones). The interoperability of Rhinoceros, Ladybug tools 1.3.0, Grasshopper and ENVI-met v.5 was demonstrated by previous research and can also ensure compatibility of results to overlap modelling of heatwaves and other SLOD risks (e.g. air pollution) within the hOA (Cadena et al., 2023).

In view of the above, according to the reference work (Cadena et al., 2023), hOA discretisation according to a grid with a spatial resolution of 5 × 5 m is assumed in HW simulation. In fact, this approach aims at limiting the exponential growth of simulation time as the grid resolution increases, although it can well represent the dimensions and typology of an hOA in the performed type of analysis (i.e., climatic conditions of open areas do not present significant variations in small spaces as it happens in indoor rooms) (Crank et al., 2018).

As an output of heatwaves simulation, maps of UTCI values within this grid are then provided. The UTCI value per grid cell is then used to assess the probability that users can occupy the related hOA area

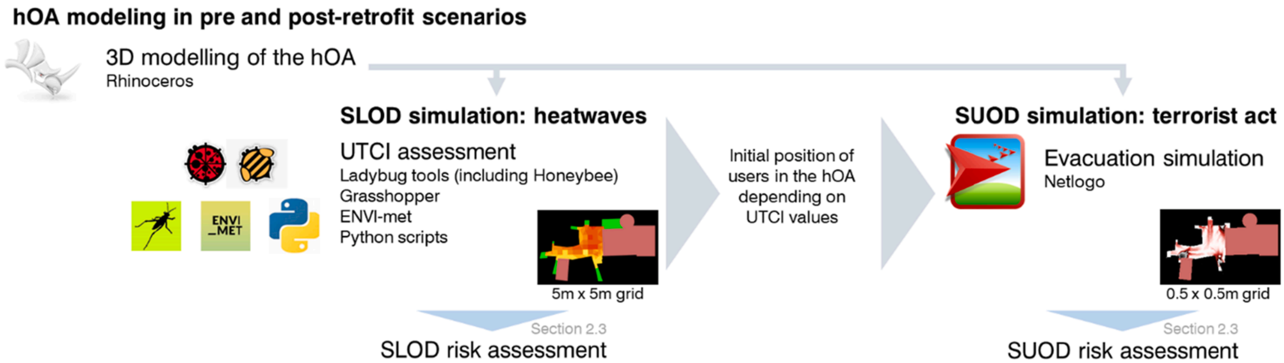

Fig. 4. Workflow for the heatwaves-to-terrorist act simulation modelling approach and related tools.

according to their thermal acceptability by Typology of users by Position PA_{tp} [%], which calculation associates different ideal outdoor permanence times by tp (OO, PO and SB) (Cheung & Jim, 2019), as defined in Eq. (2).

$$PA_{tp}[\%] = \begin{cases} -0.086UTCI^2 + 4.019UTCI + 54.119 : tp = OO(\leq 15minutes) \\ -0.249UTCI^2 + 12.914UTCI - 85.681 : tp = PO\ and\ SB(>15minutes) \end{cases} \quad (2)$$

PA_{tp} values are combined with UTCI conditions to evaluate the impact of HW on users' health according to the SLOD-related KPI discussed in Section 2.4. Therefore, in the "SLOD-to-SUOD" approach, PA_{tp} values are used to determine users' distribution in the hOA at the beginning of the evacuation process, by considering that UTCI conditions can alter the outdoor distribution of users during HW. In this sense, this work does not include individual adaptive measures to reduce heat stress, e.g. using umbrellas for shade, but consider homogeneous effects of UTCI on the user behaviours by *tp*.

The evacuation simulations are then performed through the *open-source NetLogo* platform (version 6.2.0) (Banos et al., 2015; Wilensky, 1999) using a specific terrorist act simulation model already developed and verified (Quagliarini et al., 2023b). Since this work assumes AT1 and AT2 in outdoors as attack typologies, the simulator considers that users placed indoors find themselves in a safe area and thus do not participate in the evacuation process. The model considers that hOA access streets are safe targets for evacuation. The simulated users thus select their evacuation path towards an access street according to the factors in Eq. (3), which is applied to the cell scale as basic movement scale, since the SUOD simulation model relies on a 0.5 × 0.5 m grid representing the hOA.

$$A_{c,t}[-] = w_P * P_{c,t} + w_F * F_{c,t} + w_R * R_{c,t} + w_O * O_{c,t} \quad (3)$$

In particular, each user has a specific motion direction with 200° field of view and, at a given simulation time *t*, chooses the next cell *c* (not yet occupied) by maximising the attraction factor ($A_{c,t}$) [-], which depends on four non-dimensional factors: the crowding level, that increases with user density ($P_{c,t}$), the normalised distance to the nearest evacuation target ($F_{c,t}$), the distance to the nearest cell affected by the terrorist act ($R_{c,t}$), and the normalised distance to the nearest obstacle or building ($O_{c,t}$). In the meantime, attackers move in a predator-prey logic (Li et al., 2017) (i.e., chasing users in AT1 and moving along a quasi-straight line for AT2 to increase the vehicle speed while running over the crowd). Initial attackers' positions are considered depending on the scenario creation rules (Section 2.2). In these conditions, users can have a certain probability (i.e., equal to 50 %) to suffer from the AT effects, depending on the distance from the attackers (i.e., 1 m in AT1; 3 m in AT2). Finally, the evacuation simulation ends when all the users (excluding casualties) have completed the evacuation process or when the maximum scheduled evacuation time is reached (in this study, 600 s according to previous reference research (Quagliarini et al., 2023b)).

2.4. Multi-risk assessment and mitigation strategies evaluation for heatwaves-to-terrorist act in hOAs

The results of the simulations for heatwaves and terrorist act risks are integrated using specific KPIs and risk metrics, developed starting from validated approaches in previous phases of the BE S[2]ECURe research project related to SLODs, including heatwaves (Cadena et al., 2023), and SUODs, including terrorist acts (D'Amico et al., 2024). KPIs and metrics are defined to represent the effects of risks on users' behaviours and health status, and to enhance the analysis and comprehension of the interaction between humans and the built environment, applying to different scenarios.

All the KPIs (1 for HW and 11 for T) are normalised to facilitate their comparison, and their value varies between 0 (excluded) and 1 (included). They are then combined to calculate single and multi-risk metrics using the Analytic Hierarchy Process (AHP) (Goepel, 2013), which is employed to assign priorities to the KPIs in the final metrics and to check their consistency by the consistency ratio (<10 %). In view of the use of normalised KPIs, the final value of the metrics varies between a minimum of 0 (excluded) and a maximum of 1 (included). The main issues on KPIs and Risk Metrics are provided in the following, while Appendix A offers a more detailed summary of KPIs calculation methods.

The *Heatwaves Risk* metric (*HWR* [-]) is calculated following Eq. (4), and is based on two KPIs sensitive to the users' typology by position aimed at calculating *Water Loss Risk by age and Typology of users by Position* ($WLR_{age,tp}$ [%]), which depends on typical permanence times in the hOA (i.e., up to 15 min for OO and up to 1 hour for PO and SB). This characterisation relies on the calculation of PA_{tp} shown in Eq. (2), while $WLR_{age,tp}$ is expressed as a percentage of the average individual body weight by age (Cadena et al., 2023). As shown in Eq. (4), $WLR_{age,tp}$ is also normalised by a *critical water loss WLC* [%], corresponding to 4 % and related to severe dehydration (Błażejczyk et al., 2014). In addition, a weighting factor (W_{age}) ranging from 0 to 1 is assigned to each age group based on estimated health impacts and following the AHP methodology (i.e., 0–4 years: 0.410; 5–14 years: 0.175; 15–19 years: 0.085; 20–69 years: 0.030; 70+ years: 0.300).

The final *HWR* is then obtained by combining the effects of HW on two behavioural *tp* categories (PO and SB are considered together due to the same ideal permanence time), which are associated to an equal weight w_{tp} (0.5), according to a conservative approach.

$$HWR = \sum_{tp} w_{tp} \cdot \left(\sum_{age,tp} w_{age} \cdot \left(\frac{WLR_{age,tp}}{WLC} \right) \right) \tag{4}$$

The *Terrorist act risk* (*TR* [-]) is determined as a risk vector concerning the three considered scenarios (AT0, AT1, and AT2). As shown in Eq. (5), this value results from the AHP-based weighted sum of 11 non-dimensional [-] KPIs defined by previous related works (D'Amico et al., 2024):

$$\begin{aligned} TR = & \sqrt{\left(\sum_{AT} \mathrm{TR}_{AT}{}^2 \right) \Big/ 3} \; with \; AT = AT0,\; AT1, AT2; \mathrm{TR}_{AT} \\ = & \; 0.17 \cdot \mathrm{TN}_{95} + 0.13 \cdot \mathrm{O}_p + 0.12 \cdot \mathrm{Exp} + 0.12 \cdot \mathrm{R}_{evac} + 0.11 \cdot \mathrm{R}_{RC,tot} \\ & + 0.09 \cdot \mathrm{CR} + 0.09 \cdot \mathrm{SOS} + \; 0.08 \cdot \mathrm{FN}_{95} + 0.05 \cdot \mathrm{PN} \; + 0.04 \cdot \mathrm{O}_i \\ & + 0.02 \cdot \mathrm{V}_{loss} \end{aligned} \tag{5}$$

where: TN_{95} refers to the evacuation time of the 95 % of users arrived to a safe area (to exclude outliers such as users placed too far from the safe areas or involved in marginal interactions and queuing phenomena); *Op* evaluates the degree to which urban furniture provides users with protection from attacks; *Exp* accounts for the effective number of users exposed to the attack in the whole hOA; R_{evac} tracks how many users complete the evacuation; $R_{RC,tot}$ evaluates how obstacles affect user movement; *CR* reports injuries or casualties; *SOS* analyses the availability of safe outdoor areas; FN_{95} is a comparative measure that assesses the actual flow against the optimal idealised rate (i.e., 1.5 persons/s per m of path width); *PN* quantifies physical contact during evacuation; O_i quantifies the extent to which obstacles impede movement; V_{loss} tracks the speed reduction caused by obstacles.

The single risk values *HWR* and *TR* are also combined to obtain a bidimensional multi-risk vector *MR [-]*, as shown in Eq. (6). In this work, to comprise the effects of each single risk in a conservative assessment and to provide a balanced analysis of the mitigation strategies potential, no weights are associated to *HWR* and *TR* in the final *MR* definition.

$$MR = \sqrt{\left(\mathrm{HWR}^2 + \mathrm{TR}^2\right) / \; 2} \tag{6}$$

Finally, *HWR, TR* and *MR* are used to compare pre- and post-retrofit scenarios, thus evaluating the mitigation strategies effectiveness in single and multi-risk conditions. In particular, Eq. (7) shows the percentage change of each risk metric value *PCR* [%] between pre-retrofit and post-retrofit scenarios, considering pre-retrofit values as a benchmark. In this evaluation, negative *PCR* values imply the mitigation of single and multi-risk conditions in post-retrofit scenarios.

$$PCR \; [\%] = \frac{(post \; retrofit \; value - pre \; retrofit \; value)}{pre \; retrofit \; value} \times 100 \tag{7}$$

3. Results

3.1. Pre- and post-retrofit scenarios in the case study

3.1.1. Pre-retrofit scenarios

The pre-retrofit scenario is shown in Fig. 2 as a general qualification of the hOA physical conditions, mainly providing morphological and geometrical issues, and the identification of special buildings. Concerning other parameters of the built environment affecting HW, the following albedo (α) values have been associated with the hOA surfaces by material: α=0.6 for clear calcareous blocks and α=0.4 for dark stone blocks, composing pavements, vertical surfaces and roofing; α=0.5÷0.6 for plastered buildings with clear colours, on vertical surfaces; α=0.5 for light-coloured bituminous surfaces and red tiles, while α=0.15 for dark bituminous coats, composing roofing.

Concerning HW input data, major HW effects could be associated to the summer period between the end of June and the beginning of July, which statistically includes the hottest weeks of the year (Martinelli et al., 2024). According to 5-years monitored data,[2] this work considers the 11th of July, from 11AM to 4PM, as the most critical condition for simulation (hottest day of the year in Bari climate conditions).

Concerning T input data, besides the baseline scenario AT0, Fig. 5 outlines attack points for AT1 and AT2 (red dots), and it also traces, for AT2, the possible straight-line trajectory of the vehicle running over the crowd (dashed arrow). In particular, the points of attack are focused on the cathedral parvis. Here, the high symbolism of the church, combined with the highest possible crowding level of users waiting to access the building, external tourists and passers-by, makes this sub-area the most vulnerable one as the main attracting element for perpetrators.

According to Section 2.2, these conditions are assumed for both pre- and post-retrofit scenarios.

Concerning users' exposure and vulnerability, Fig. 6A shows that the outdoor density D_{out} trend over time for holidays is characterised by general higher values with respect to working days, since holidays are widely affected by visitors' presence in the cathedral, also due to religious services. Peak conditions in D_{out} values mainly happen within the timespan from 11AM to 4PM, which is also the critical period for HW scenarios. This data remarks the significance of a heatwaves-to-terrorist act combination (i.e., HW-to-AT0, HW-to-AT1 and HW-to-AT2). Fig. 6B shows, instead, the characterisation of users' individual vulnerability in terms of their position in the built environment, focusing on holidays in view of the higher exposure level. In Fig. 6B, the position ratio *PR* is offered with respect to the aggregation of the three Typology of users by Position defined in Section 2.2, namely OO, PO and SB. In the timespan from 11AM to 4PM, several peak conditions are related to the presence of most of the users in outdoors (i.e., compare *PR* for OO+PO+SB), with a prominent effect due to SB. In view of the above, to consider multi-risk critical conditions in the hOA, the timespan from 11AM to 12PM has been considered in pre-retrofit scenarios, leading to a total of about 1465 users within the square exposed to the direct effects of HW and ATs, of which 1340 SB and 125 OO+PO.

Finally, the user individual vulnerability by age has been derived from population statistics for Bari urban area,[3] using thus rapid assessment methodologies which lead to assuming a constant distribution of users by age over time. In particular, 30 % of users belong to vulnerable classes, i.e., 0–4 years (toddlers, hand-assisted by parents)=3 %; 5–14 years (children, assisted by parents)=8 %; 70+ years (autonomous elderly)=19 %. In addition, young autonomous users (15–19 years) represent 5 % of users, while adults (20–69 years) represent the most frequent age-related class (65 %). According to Section 2.2, these conditions are assumed for both pre- and post-retrofit scenarios.

3.1.2. Post-retrofit scenarios

Table 2 correlates the macro-classes of mitigation strategies outlined in Section 2.2.2 with their compatibility with the historical place of Piazza dell'Odegitria, depending on regulatory framework of Bari.[4] Suitable strategies are then outlined in the last column of Table 2.

[2] www.arpa.puglia.it (last access: 12/02/2025)

[3] https://demo.istat.it/?l=en (last access: 05/07/2024)

[4] "Detailed Executive plan" (Piano Particolareggiato di esecuzione – available at https://www.comune.bari.it/documents/114869/648857/Piano+Particolareggiato+della+Citt%C3%A0+Vecchia+%5BPP%5D.+Nta+Quartiere+San+Nicola.+Piano+particolareggiato+di+esecuzione+%28soppressione+art.45+Nta%29.doc/d4d83d71-2783-4725-bd66-24e4802b21e8) and the Technical normative framework in the "Regional plan for landscape" (PPTR of Apulia Region - available https://cartografia.sit.puglia.it/doc/PUTTp_NTA_coordinate.pdf).

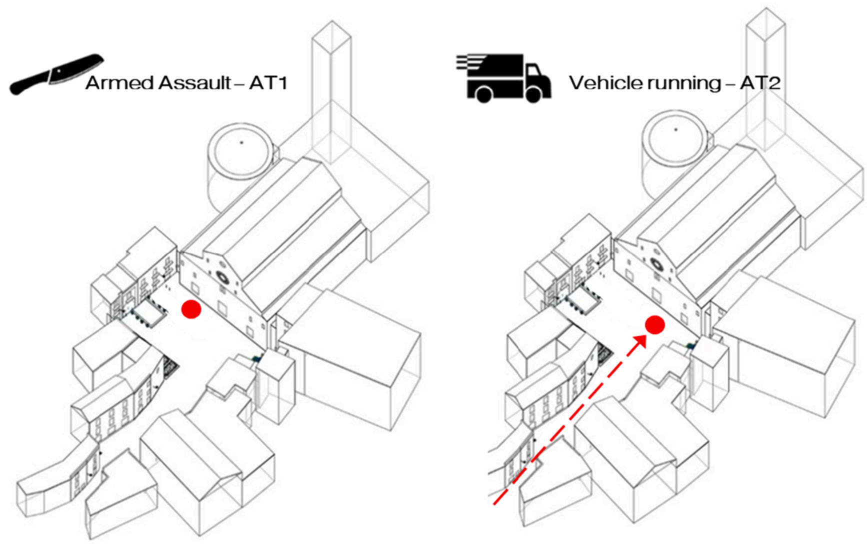

Fig. 5. Outlines of terrorist act scenarios, defining attack points (red dots) and vehicle direction in accessing the hOA in AT2.

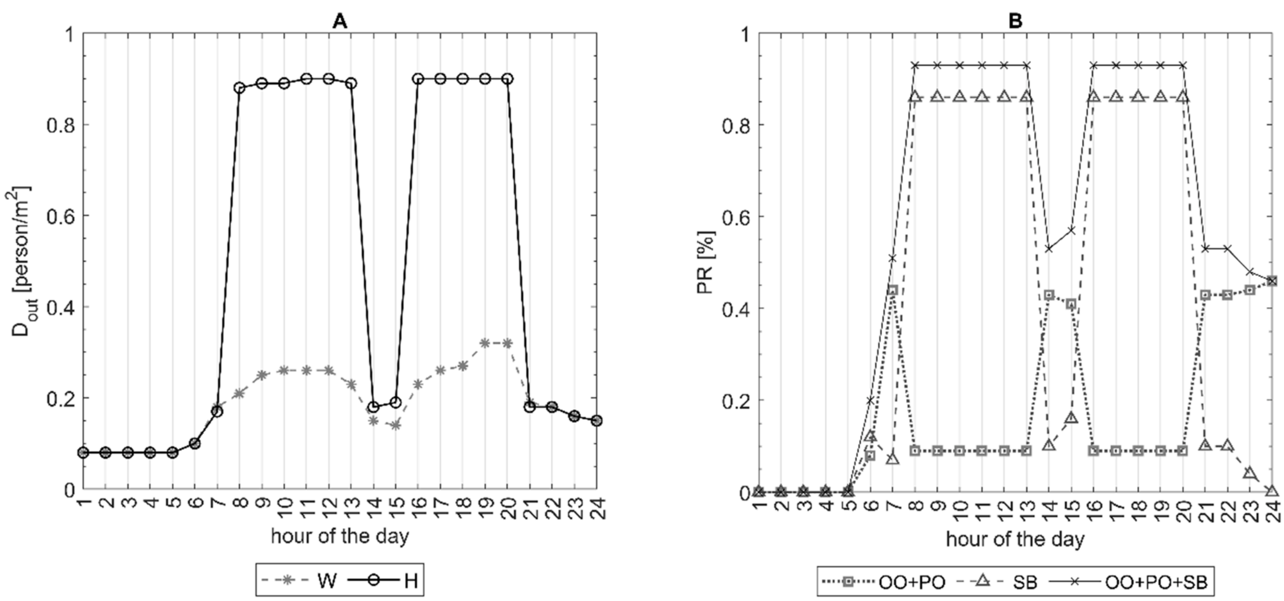

Fig. 6. Users' exposure and individual vulnerability assessment over time for typical working days (W) and holidays (H): A- crowding levels in terms of outdoor density D_{out} [person/m^2]; B- position ratios PR [%] for only outdoor and prevalent outdoor users (OO+PO), users of the special buildings (SB) and their overall effect (OO+PO+SB), calculated with respect to the overall number of users in the hOA.

Table 2 outlines the four main solutions for the application to the case study, according to the general implementation layouts in Fig. 7. "Trees" are located far from the façades of churches, but at the same time, along the possible vehicle path in the AT2 scenario, in order to maximise their efficacy as an obstacle to the vehicle. Similarly, "Mobile or fixed barriers combined with green elements" are distributed along the vehicle path, reducing the width of the driveway entrance and thus preventing free access to the hOA. "Seasonal shadings" are located above the outer space of the bar near the church, limiting the introduction of these new elements within the square while supporting PO users in HW scenarios. Finally, for "Cool pavement", the clear calcareous paving material is re-introduced to replace the dark one within the overall extension of Piazza dell'Odegitria (brown area in Fig. 7). The mitigation strategies based on vertical surfaces retrofit have been excluded due to poor adherence to the local regulatory framework, as well as considering the good optical performances of the existing walls finishing with respect to HW.

To model HW-affecting parameters, the following albedo (α) values have been associated with the hOA surfaces by material: α=0.8 for "Mobile or fixed barriers" and α=0.2 for the combined "green elements"; α=0.18 for "Trees"; α=0.6 for "Cool pavements"; α=0.65 for "Seasonal shadings".

Finally, these strategies are also considered in a combined manner, overlapping their implementation according to the general layout in Fig. 7.

3.2. *Multi-risk assessment and mitigation strategies effectiveness in the case study through heatwaves-to-terrorist act behavioural simulation*

Fig. 8 summarizes the general hOA layouts in pre-retrofit and post-retrofit scenarios (considering both the single strategies of Table 2 and their combinations), alongside the main SLOD simulation outputs in HW

Table 2
Summary of strategies for the mitigation of HW and T risks according to Section 2.2.2, and correlation with their implementation in the case study of Piazza dell'Odegitria. The compatibility with the cultural relevance of the case study is discussed, coherently with the local regulatory framework. "n.a.": not assessable on the basis of the current reference regulatory framework.

Strategy	Applicability for regulatory framework	Suitable strategy
Trees	Executive Plan (*Art. 4*): Planting of a compact group of medium-sized trees (holm oaks or similar)	yes
Seasonal shadings	*n.a.*	yes
Cool pavement	Executive Plan (*Art. 47*): restoration of paving in limestone or basaltic stone in the "Città Vecchia district" in Bari	yes
Mobile or fixed barriers combined with green elements	Executive Plan (*Art. 49*): Any bollards, installed to delimit pedestrian areas, must be made up of stone hemispheres or cast-iron columns, possibly connected by chains	yes
Cool façade	Exposed stone in façade should be guaranteed to maintain the formal relevance (PPTR, Apulia Region). For plastered façade, clear colors are accepted (PPTR, Apulia Region)	yes, if tiny and transparent layers are applied
Green walls	Exposed stone in façade should be guaranteed to maintain the formal relevance (PPTR, Apulia Region)	no

conditions, which are shown as UTCI distribution maps using the 5 × 5 m resolution grid defined in Section 2.3. The UTCI distribution roughly traces the effects of HW on users' health: the lower the UTCI values (and thus lighter the colour in Fig. 8), the lower the $WLR_{age,tp}$ values and thus the final *HWR*. $WLR_{age,tp}$ values are reported in the supplementary material S1 for completeness, while *HWR* values are reported in Fig. 9, together with *TR* and *MR* values and *PCR* for single and multi-risk conditions.

The comparison between pre- and post-retrofit results shows very slight significant improvements for the single strategies, highlighting how the climatic context, the geometry and the orientation of the square, and the materials of the building surfaces seem to have a predominant influence compared to the adopted mitigation strategies. However, observing the UTCI maps and the *HWR* results in Fig. 9, it can be noticed that "Cool pavement" has the greatest impact in reducing the risk, especially on transient users, by providing a widespread, although not so significant, mitigation of UTCI levels. On the other side, the introduction of "Trees" demonstrates a positive impact on *HWR*, but in a more "scattered" way and coherently with the trees' position. Similar assumptions can be provided for "Seasonal shadings", which are mainly placed in a specific area of the square according to the outdoor areas use. The simulation-based assessment of combined mitigation strategies against SLOD mainly underlines the major positive impact of the joint implementation of "Cool pavement" and "Trees" (including or not the barriers displacement), which leads to HWR=0.24 (Fig. 9).

Thanks to the UTCI maps, Fig. 8 also provides an overview of the users' distribution in outdoors depending on PA_{tp} values. In general, the higher the UTCI value by area, the lower the probability that a typology of users (OO, or PO and SB) can occupy this area while staying in outdoors. According to Fig. 8, UTCI values range from 31 °C (light yellow) to 36 °C (red), and thus PA_{tp} values range from 87 % to 96 % for OO and from 57 % to 75 % for PO and SB. These SLOD simulation outputs are then used to populate users' positions in SUOD simulations, as remarked in Section 2.2. According to Fig. 8 and the aforementioned discussion on the impact of single and combined strategies, users' initial positions could be considered more widespread in the case of "Cool pavement" implementation since UTCI maximum values are generally about 2 °C lower than in the other cases. Nevertheless, it should be noticed that in

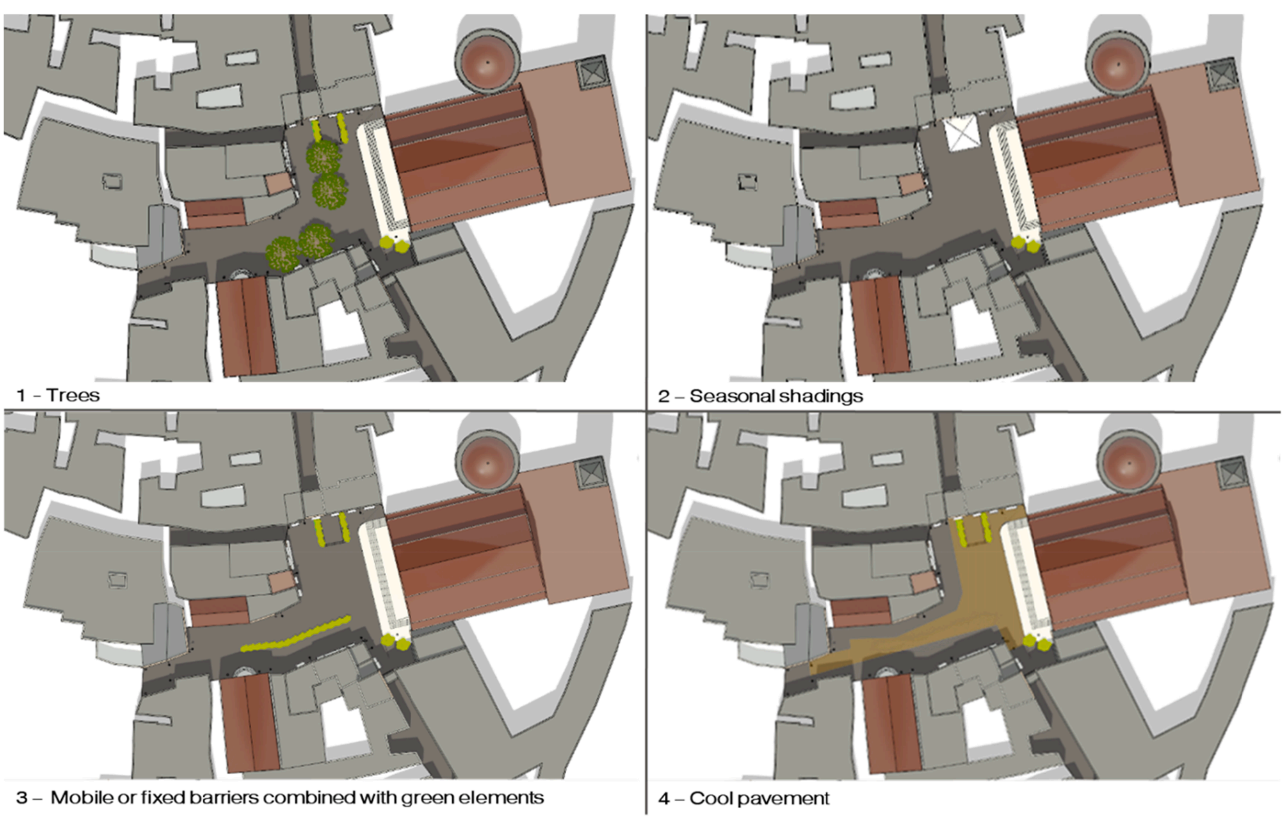

Fig. 7. Typologies of selected strategies and general implementation layout.

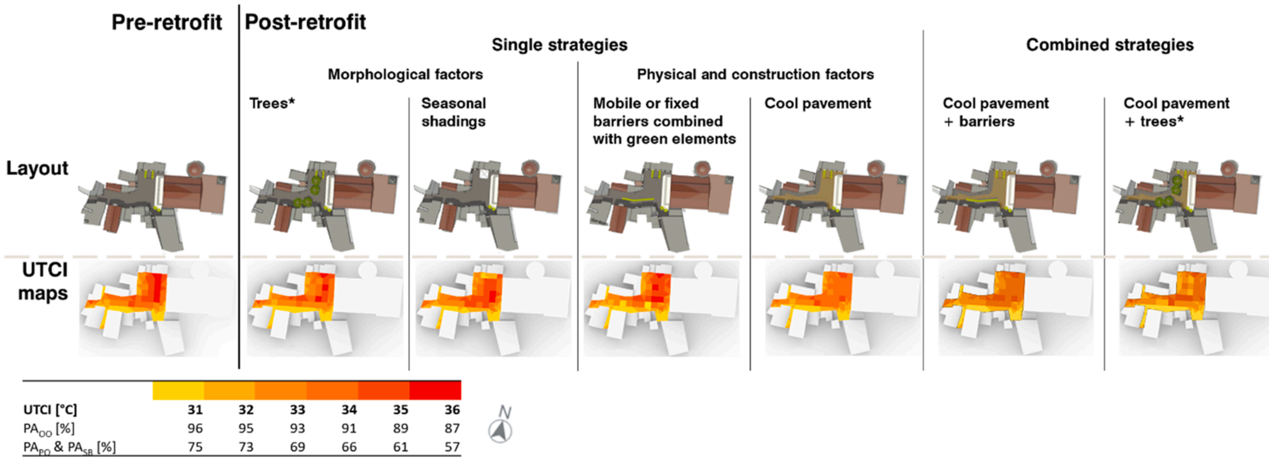

Fig. 8. hOA layout in pre-retrofit and post-retrofit (by single and combined mitigation strategy) scenarios, and UTCI distribution map, including legend on UTCI and outcoming PAtp values by colour. *: UTCI distribution, and thus HWR effects, are the same for the combination with barriers.

	Pre-retrofit	Post-retrofit							
		Trees	Seasonal shadings	Barriers	Cool pavement	Cool pav. + barriers	Cool pav. + trees	Trees + barriers	Trees + cool pav. + barriers
WLR for PO & SB [-]	3.37	3.35	3.37	3.37	3.37	3.37	3.31	3.37	3.31
WLR for OO [-]	4.81	4.74	4.81	4.81	4.71	4.74	4.62	4.74	4.62
HWR [-]	0.247	0.245	0.247	0.247	0.244	0.245	0.24	0.245	0.24
PCR on HWR [%]		-0.81%	0.00%	0.00%	-1.21%	-0.81%	-2.83%	-0.81%	-2.83%
TRAT0 [-]	0.21	0.21	0.21	0.20	0.21	0.20	0.21	0.20	0.20
TRAT1 [-]	0.47	0.45	0.47	0.43	0.47	0.43	0.45	0.42	0.42
TRAT2 [-]	0.43	0.40	0.43	0.22	0.43	0.22	0.40	0.22	0.21
TR [-]	0.387	0.368	0.387	0.302	0.387	0.302	0.368	0.297	0.295
PCR on TR [%]		-4.93%	0.00%	-22.06%	0.00%	-22.06%	-4.93%	-23.28%	-23.91%
MR [-]	0.455	0.437	0.455	0.394	0.454	0.383	0.435	0.392	0.38
PCR on MR [%]		-3.96%	0.00%	-13.41%	-0.22%	-15.82%	-4.40%	-13.85%	-16.48%

Fig. 9. Summary of single to multi-risk conditions in pre- and post-retrofit scenarios, including both single strategies and their assessed combinations.

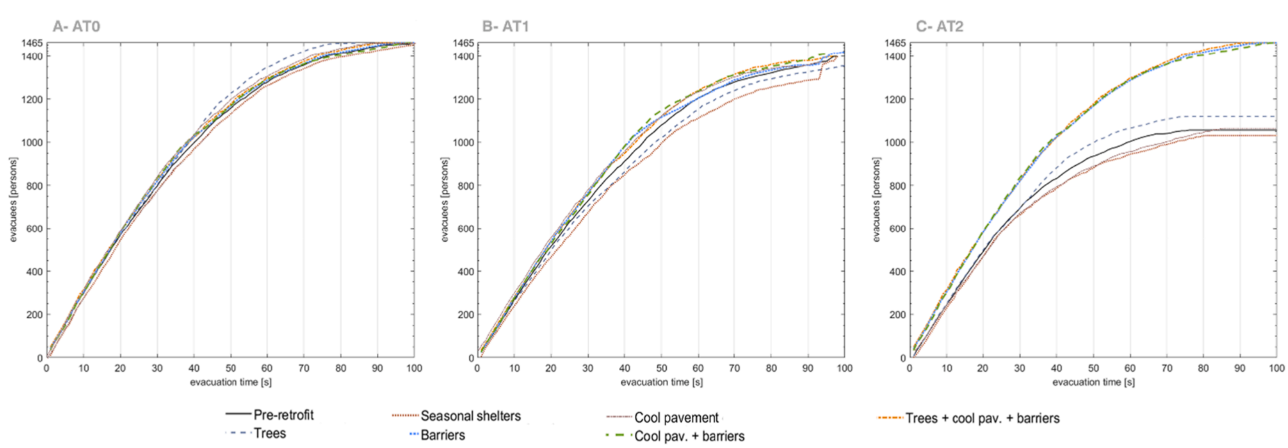

Fig. 10. Evacuation curves in main pre- and post-retrofit scenarios by attack typology: A-AT0, B-AT1, C-AT2.

these conditions more users would probably be placed along the vehicle trajectory in AT2. Therefore, it is expected that the general *TR* values will not decrease. Scenarios with "Seasonal shadings" and barriers do not consistently modify the PA_{tp} values in the 5 × 5 m grid, while "Trees" have a scattered effect on users' positioning, especially for PO and SB since their PA_{tp} increases more than the one of OO (Fig. 8).

Given these impacts on users' positioning in SUOD evacuation simulation, Fig. 10 shows the median evacuation curves for the different types of attack AT for both pre- and main post-retrofit conditions, thus providing an overview of the rapidity of the process in terms of users who evacuated the hOA over the simulation time. The evacuation curves show both single strategies and their most impactful combinations in terms of movement process. The specific KPIs defined in Section 2.4 are reported, by simulation scenario, in Supplementary Material S2.

Apart from the scenarios implementing barriers, which prevent vehicle access to the inner part of the square, more critical conditions are generally observed in the case of a vehicle attack AT2 (Fig. 10-C) since the greatest number of users is positioned along the vehicle's trajectory. In AT2, the final number of evacuees who arrived at a safe area (i.e., one of the hOA accesses) is significantly higher in barrier-retrofitted scenarios. For this reason, additional strategies combined with barriers seem to have a similar impact in terms of the evacuation process due to the prominent effect of the barriers themselves. As expected, AT1 scenarios have a limited relevance in terms of users who cannot complete the evacuation (being part of casualties) due to the attack typology, which relies on a close proximity between the perpetrators and the users. Moreover, in AT0 and AT1, median evacuation curves are close one to the other. This result underlines that the initial positioning of users is quite similar, too, since the strategies implementing barriers have a secondary impact on UTCI mitigation (as discussed in Fig. 8), while the small differences in the curve rapidity and in the final number of evacuees (i.e., for AT2 - Fig. 10-C) are limitedly due to a more widespread or focused presence of users in the initial attack areas. Finally, it could be noticed that, in both AT1 and AT2, barriers can have a mitigation impact as immediate protection of users from the attack source (see Supplementary Material S2). Moreover, they seem to imply a channelling of users while moving towards the hOA accesses, thus improving flows towards safe areas.

Fig. 9 offers the overall summary of the single risk metrics *TR* for terrorist acts in the pre- and post-retrofit contexts, considering both the single strategies and their combinations. In particular, Fig. 9 confirms, from a broader perspective, the negligible impact of “Cool pavement” and “Seasonal shadings” when applied by themselves. On the contrary, “trees” and “barriers" can reduce *TR* risk not only from the standpoint of the evacuation curves but also from the overall interaction among the users, the attackers and the hOA since they are also the presence of relevant obstacles placed in different parts of the hOA.

Finally, Fig. 9 also combines the single risk assessment indexes into the final MR assessment, including multi-risk *PCR* by single and combined strategies. In particular, since “Mobile or fixed barriers combined with green elements” can have the highest mitigation impact on *TR, MR* significantly decreases for all the strategies that include them in the final hOA layout. In general terms, although multiple mitigation strategies could additionally reduce *MR*, it is also worth noting that slight *PCR* variation occurs between the implementation of “barriers” by themselves and their combination with other compatible solutions (i.e., cool pavement and trees[5]). Moreover, most of the *MR* reduction for the combination of cool pavement, trees and barriers is due to the impact of these strategies on *HWR* rather than on *TR*. In this sense, most of the variation in the initial SLOD-related users’ distribution in the hOA due to the UTCI conditions is determined by the widespread effect of cool pavement and the more “scattered" one of trees, while barriers have a negligible impact. Thus, overlapping these strategies seems not to significantly alter the conditions in the most critical square area for AT1 and AT2 with respect to the combination of barriers with trees, as qualitatively remarked by UTCI values in Fig. 8.

4. Discussion and final remarks

The methodology proposed in this work uses behavioural simulation models to assess single to multi-risk levels in hOAs due to SLOD (i.e., heatwaves HW) and SUOD (i.e., terrorist acts T) and to perform an effectiveness analysis of single and combined mitigation strategies. In particular, this work focuses on a significant square in the Mediterranean area (Piazza dell’Odegitria, Bari, Italy) to showcase the approach capabilities.

In view of the above, the results firstly present significant key findings on the case study application (Section 4.1), thus providing a response on how solutions for heatwaves risk mitigation can reduce terrorist risk in hOAs. Then, lessons learned from the case study are used to offer general insights on other hOA applications in terms of solutions sustainability in similar heatwaves-to-terrorist act application scenarios (Section 4.2). Finally, further research efforts are suggested to improve the level of knowledge on multi-risk reduction potential in view of the general SLOD-to-SUOD behavioural simulation-based approach (Section 4.3).

4.1. Key findings on the case study application

Single mitigation strategies generally lead to specific single risk mitigation. This result seems to imply that single strategies mainly oriented towards HW could have a very limited effect on T conditions. In particular, “Cool pavement” seems to mainly reduce HW risk (mitigating critical temperature conditions in the hOA), while having a negligible effect on T risk (since they do not reduce the presence of users inside the critical attack areas). On the contrary, “Mobile or fixed barriers combined with green elements” have a great impact on T risk (representing a barrier towards attackers, possibly protecting users from the attack source, and channelling users’ flow towards the hOA accesses as safe areas), while their impact on HW is negligible (since they do not effectively mitigate outdoor temperature conditions). An effective multi-risk mitigation strategy is represented by concerns the implementation of “Trees", which provides both the reduction of air temperature and the presence of obstacles to the attackers, even though the scattered position of these elements inside the hOA limits the overall effectiveness against HW (about −1 % of mitigation potential) and T (about −5 %).

As expected, combined mitigation strategies can have a major impact when compared to single risk scenarios, since they can integrate the respective mitigation effects on SLOD and SUOD risks (Rosso et al., 2023). The implementation of these kinds of multiple strategies can also lead to redundancy criteria, boosting risk mitigation even in case of potential failure of one of them (e.g., poor maintenance of a solution over time) (Castaño-Rosa et al., 2022; Komendantova et al., 2014). In the case study, this result is mainly relevant considering the effectiveness of trees and cool pavement on HW mitigation, combined with barriers to significantly reduce TR thanks to their displacement to hinder AT2 and provide support and protection to users during AT1 evacuation. However, multiple strategies show less effectiveness than expected for multi-risk conditions. In particular, the compatible strategies selected for Piazza dell’Odegitria have demonstrated a limited impact on HW risk. This result could be due to the specific characteristics of the case study, and in particular to the overall hOA morphology (including the low ratio between buildings’ height and width of the surrounding spaces), the geographical location and the climatic conditions (Salvati et al., 2019; Ahmed et al., 2024; Fahed et al., 2020), which prevent a homogeneous reduction of the UTCI distribution in the hOA, thus leading to relevant effects on PO and SB who spend a lot of time in the square.

Finally, although having a potentially relevant impact in such a Mediterranean context, interventions on the buildings’ materials and surfaces have not been considered due to their lower compatibility with the conservative policies applied at the local scale.

4.2. Insights on the sustainability of single and multiple strategies

Coupling of mitigation strategies is in line with the recommendations of general risk reduction guidelines for the historical built environment. Nevertheless, the artistic, architectural, social and historical value of hOAs obviously imply complex solutions to balance risk mitigation and preservation.

Considering the historical and architectural features of the case study hOA, and thus of similar ones in the Mediterranean area, it could be remarked that fixed or mobile barriers integrated with green elements could be one of the best strategies to mitigate multi-risk conditions. In fact, as discussed above, even if their impact on HW risk is negligible, other solutions could not have a significant effectiveness on this hazard due to the hOA characteristics. On the contrary, among all the assessed strategies, barriers have the highest and most sensible effect on the reduction of T risk (>20 %). Moreover, these elements can be easily installed in the hOA adopting highly reversible techniques. As for

[5] Seasonal shadings are not herein combined with other strategies since they imply a significant initial concentration of users in a risk prone area.

multiple strategies, the joint application of cool pavement is associated with high compatibility with the hOA identity in terms of colours and materials. Moreover, adding cool pavement provides support against HW risk, although limited. The additional implementation of trees in the hOA layout could increase the multi-risk mitigation potential, but it could pose questions about the compatibility of this solution with the original square identity, since these elements could alter the sights in the hOA, especially to the ones towards the cathedral.

In view of the above, results suggest that participatory approaches should be linked with the proposed simulation-based one (Castaño-Rosa et al., 2022). Considering that historical contexts are sensible to preservation and own a high social identity, ensuring the involvement of stakeholders and citizens in the decision process allows decision-makers to evaluate the level of appreciation of the simulated strategies. Decision-makers could thus use simulation-based strategies for the pre-selection of complex and multiple mitigation solutions, which will transform the hOA itself. Then, the evaluations for choosing the strategies to be applied should be integrated not only with the social standpoint (acceptability of place transformation, through participatory approaches), but also with economic (feasibility), functional (business continuity and compatibility of new hOA features with its typical/new use), architectural and operational (on-site deployment and effective reversibility of intervention) factors (Castaño-Rosa et al., 2022; Gupta H et al., 2024).

4.3. Limitations and future research

This work aims at providing a case-study oriented showcasing of the "SLOD-to-SUOD" simulation-based approach for single and multi-risk assessment and mitigation, determining how mitigation strategies mainly intended for HW can also impact T risk reduction in scenarios affected by a combination of these two hazards. This approach is useful for accelerating the emergency analysis process in complex built environment, even by decision makers and technicians with limited knowledge of specific multi-risk issues and modelling of user behavioural effects. In this sense, the study represents one of the first efforts to model and assess emergencies with different raising timings, but which may be overlapped in both space and time (Curt, 2021).

Moreover, the applied methodology allows decision-makers to assess the impact of mitigation strategies not only with respect to the specific SLOD/SUOD for which they are designed, but also for other risks that may occur in the hOA. This approach could then be extended by future research to other typologies of hOAs besides squares, as well as to single buildings or urban areas. Depending on the scale of analysis, other models could be employed using the same logic of this work.

In this sense, it should be noticed that:

- The methods for scenario creation could be affected by some simplifications in the representation of the complexities of the built environment and of its users. The hOA is herein investigated by itself, and thus the achieved results could be considered not exhaustive of the expected scenarios, since they do not include the analysis of the entire historic centre where the hOA is placed, and of other possible factors resulting from non-expeditious analyses. Further efforts to model the hOA use and its main features by in situ surveys (mainly for users' vulnerability and exposure analysis) could then be provided to improve the reliability of input scenarios, also considering the overall urban dynamics in HW scenarios.
- Current methods provide some reliable but simplified assumptions in HW modelling that could be improved to investigate additional input conditions for T scenarios and their evacuation simulation. In particular, the model uses a 5×5 m grid for HW simulation outputs, to balance computational efforts and outputs' reliability, but finer grids could be considered to describe additional local HW effects on the users. The model also uses UTCI as the main driver for the prediction of HW effects on user health and their outdoor distribution, but additional parameters and approaches could be tested (e.g., Standard Predicted Mean Vote to identify users' distribution through interviews quantifying discomfort in the different areas of the hOA, Physiologically Equivalent Temperature to analyse the presence of areas which reproduce a comfortable indoor setting thus increasing the probability of users moving towards them) (Walls et al., 2015). Future efforts to include individual thermal adaptive behaviours should be provided, moving from homogeneous HW effects on the whole population to the inclusion of protective actions at the user level depending on the individual risk awareness and perception. Similarly, behavioural modelling for terrorist act response could include specific safe behaviours, cognitive and emotional elements, as well as other crowd phenomena (such as leadership effects also in relation with the modelling of first responders) (Cao et al., 2022; Bakhshian & Martinez-Pastor, 2023; van der Wal et al., 2017).
- The analysed post-retrofit strategies just represent examples of potential solutions in the hOA context, based on the specificities of the case study. The assessed strategies are selected in terms of compatibility with the hOA, and they focus on its public spaces, which can be directly involved in local administration interventions. Therefore, additional strategies could be chosen and deployed in future research, firstly including those related to the building façade, also in terms of joint public-private interventions on buildings, as well as to those related of private outdoor spaces linked with the hOA. In addition, especially considering T mitigation, the combination risk prevention and control strategies (including the combination of control systems with management solutions) should be investigated. The impact of evacuation and emergency planning and the active role of first responders (including Law Enforcement Agencies) should be comprised with the simulation model (jointly acting on the creation of new agents in the evacuation simulation model). These T-oriented strategies could be evaluated in combination with the tested structural measure also oriented towards HW.
- The selected strategies are assessed on the basis of their impacts on HW and T scenarios, but they could have additional mitigation potential against other kinds of emergencies (e.g., floods, earthquakes), regardless of their combination with the analysed ones.
- In view of the above, additional applications to real-world case studies with different input conditions in terms of SLOD, SUOD, hOA features, and users' characteristics should be provided to deeply investigate the potentialities of the proposed methods and to promote good practices for decision-makers. Thanks to these analyses, the multi-risk assessment of different hOAs would also promote the development of common solutions repositories, to be then tailored to each built environment depending on its physical, usage, historical, identity, social/economic/cultural features.

CRediT authorship contribution statement

Gabriele Bernardini: Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gessica Sparvoli:** Writing – original draft, Visualization, Formal analysis, Data curation. **Elena Cantatore:** Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Silvana Bruno:** Writing – original draft, Visualization, Formal analysis, Data curation. **Fabio Fatiguso:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Ilaria Isacco:** Writing – original draft, Visualization, Formal analysis, Data curation. **Graziano Salvalai:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Enrico Quagliarini:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition.

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.

Acknowledgements

This work was supported by the MIUR (the Italian Ministry of Education, University, and Research) Project BE S^2ECURe - (make) Built Environment Safer in Slow and Emergency Conditions through behavioUral assessed/designed Resilient solutions (Grant number: 2017LR75XK).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2025.106412.

Appendix A. Key Performance Indicators (KPIs) for SLOD and SUOD assessment

Table A1 summarizes the KPIs used for the SLOD and SUOD analysis, which have been selected according to the related literature reference to describe different leading phenomena in evacuation. Table A2 resumes the parameters in the equations. Further details are reported in reference works (Grissom et al., 2019; Arrighi et al., 2023).

Table A1
SLOD and SUOD-related KPIs.

Name (Ref.)	Equations	H	T
HW - Water loss (Cadena et al., 2023)	$WLR_{age} = WL_{OA}/body\ weight_{age} \times 100$ $WL_{OA} = [\sum_{a=0}^{n}(Sweat\ rate_a \cdot (t_{crit,a} \cdot A_a \cdot PA_a))]/[(\sum_{a=0}^{n} A_a) \cdot t_{crit,tot}]$ For HWR, see Equation 4; data are referred to mean (males and female) conditions	x	
$R_{RC,tot}$ - Road resistor coefficient (Zhang et al., 2015)	$R_{RC,\ tot.} = [\sum(R_{street})]/number\ of\ access\ streets$		x
V_{loss} - Pedestrian speed conservation (León and March 2014)	$V_{loss} = [\sum(v_{loss})]/number\ of\ access\ streets$		x
O_i - Obstacle friction rate (Álvarez et al., 2018)	$Oi = \frac{\sum_j (L_o \cdot \alpha_j)}{\sum_t L_{evt}} \cdot 100$		x
SOS - Temporary Secure Open spaces (Tumini et al., 2017)	$SOS = \frac{[(\sum_i A_i) + A_{SB}]}{[\sum_i (A_i \cdot UO_{od}) + (A_{SB} \cdot UO_{SB})]}$		x
Exp - Exposure index (Bernabei et al., 2021)	$Exp = \frac{Exp_T}{Exp_{max}}$		x
TN_{95} - Normalized Evacuation time (95th percentile of evacuees) (D'Orazio et al., 2015; Quagliarini et al., 2023b)	$TN_{95} = \frac{Evacuation\ time\ (95^{th})\ of\ users}{max simulation\ time\ (600s)}$		x
PN - Crowd effects (Quagliarini et al., 2023b)	$PN = \frac{(n.\ of\ physical\ contacts\ among\ users/T95)}{(5\%\ of\ users\ placed\ outdoors)}$		x
FN_{95} - Mean flow rate at the exit (Quagliarini et al., 2023b)	$FN_{95} = \max\left(0,\ 1 - \left\{\frac{[F95/\sum(access\ streets\ width)]}{(1.5 persons/s/m)}\right\}\right)$		x
R_{evac} - Number of Evacuees for SUOD from surrounding buildings in the hOA (Quagliarini et al., 2023b)	$R_{evac} = 1 - \frac{number\ of\ evacuees\ arrived\ in\ a\ safe\ area}{number\ of\ participating\ evacuees}$		x
CR - Number of deaths/casualties (Quagliarini et al., 2023b)	$CR = \frac{number\ of\ casualties}{number\ of\ outdoor\ users \cdot (1 - SAP)}$		x
O_p - Obstacle protection rate (Zhu et al., 2020)	$O_P = \frac{\sum_j (Ss_j \cdot ps_j)}{St \cdot NU}$		x

Table A2
Definition of parameters in the KPIs equations shown in Table A1.

Parameter	Definition (reference for calculation)	Unit of measure
WL_{OA}	Users' possible averaged water loss in the outdoors of the hOA	[g/h]
$Sweat\ rate_a$	Sweat rate associated with UTCI stress (and thus heat stress) for a given age category, within the specific sub-area a of the hOA	[g/h]
A_a	Outdoor area of the hOA characterized by a given UTCI condition (and with a given sweat rate)	[m^2]
PA_a	UTCI effects on users' 1-hour or transient behaviours (users' thermal acceptability probability), calculated according to Eq. (2)	[%]
$t_{crit,a}$	Reference permanence time for users in a specific sub-area a of the hOA. In this work, $t_{crit,a}$ is equal for all the square area, thus being simplified by $t_{crit,tot}$	[h]
$t_{crit,tot}$	Users' permanence time in the square (total exposure time), that is 0.25 h for passersby (15 min) and 1 h for prevalent outdoor users	[h]
WL_{age}	Individual physiological conditions for the specific risk of water loss by age group (average value for males and females)	[%]
R_{RC}	Ratio between 1 m and average width of the 1st meter of the evacuation road (thus considering the road access only)	[m/m]
v_{loss}	Ratio between the individual speed as an effect of road slope and traffic level, and the ideal walking free-flow speed (1.4 m/s)	[m/s]
L_o	Total width of the obstacles (calculated as the sum of the width of each obstacle) along a given evacuation path in a given direction	[m]
L_{evt}	Total width of the evacuation path in a given direction	[m]
α_j	Speed reduction factor associated with the typology of obstacle j having the specific L_o	[-]
A_i	Safe area of the square (areas without risks for occupants, such as direct terrorist act-induced damage)	[m^2]
A_{SB}	Special building area	[m^2]

(continued on next page)

Table A2 (*continued*)

Parameter	Definition (reference for calculation)	Unit of measure
UO_{od}	User density for the outdoor areas (only)	[persons/ m^2]
UO_{SB}	User density coefficient for the Special Building (i.e. Churches)	[persons/ m^2]
Exp_T	Normalized exposure for terrorist act risk in the square according to (Bernabei et al., 2021), that is mainly considering users placed in the outdoors (since they are essentially susceptible of attack effects)	[-]
Exp_{max}	Maximum normalized exposure in the square according to (Bernabei et al., 2021)	[-]
SAP	Self-aided percentage of users who can evacuate in case of terrorist act (in this work, 50 %, see Section 2.2)	[%]
Ss_j	j-th safe area provided by an element (e.g., monument, barrier) that comes between the attacker and the user	[m^2]
Ps_j	Number of users present in the j-th safe area as the multiplication between Ss_j and the related user density	[persons]
St	Total area of the square bounded by the built fronts and crossings	[m^2]
NU	Total number of users in the square	[persons]

Data availability

Main data from simulations supporting results and key findings are included in Supplementary Materials. Additional detailed data are available from the corresponding author, E.C., upon reasonable request.

References

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

Ahmed, N. M., Altamura, P., Giampaoletti, M., Hemeida, F. A., & Mohamed, A. F. A. (2024). Optimizing human thermal comfort and mitigating the urban heat island effect on public open spaces in Rome, Italy through sustainable design strategies. *Scientific reports, 14*, Article 19931. https://doi.org/10.1038/s41598-024-65794-8

Amarnath, G., Amarasinghe, U. A., & Alahacoon, N. (2021). Disaster risk Mapping: A desk review of global Best practices and evidence for South Asia. *Sustainability, 13*, Article 12779. https://doi.org/10.3390/su132212779

Arrighi, C., Tanganelli, M., Cristofaro, M. T., Cardinali, V., Marra, A., Castelli, F., & De Stefano, M. (2023). Multi-risk assessment in a historical city. *Natural Hazards, 119*, 1041–1072. https://doi.org/10.1007/s11069-021-05125-6

Błażejczyk, K., Baranowski, J., & Błażejczyk, A. (2014). Heat stress and occupational health and safety – spatial and temporal differentiation. *Miscellanea Geographica - Regional Studies on Development, 18*, 61–67. https://doi.org/10.2478/mgrsd-2014-0011

Bakhsh, K., Rauf, S., & Zulfiqar, F. (2018). Adaptation strategies for minimizing heat wave induced morbidity and its determinants. *Sustainable Cities and Society, 41*, 95–103. https://doi.org/10.1016/j.scs.2018.05.021

Bakhshian, E., & Martinez-Pastor, B. (2023). Evaluating human behaviour during a disaster evacuation process: A literature review. *Journal of Traffic and Transportation Engineering (English Edition), 10*, 485–507. https://doi.org/10.1016/j.jtte.2023.04.002

Banos, A., Lang, C., & Marilleau, N. (2015). *Agent-based spatial simulation with netlogo*. Elsevier.

BE S2ECURe. (2024) Accessed 20 Nov www.bes2ecure.net Accessed 20 Nov.

Bernabei, L., Mochi, G., Bernardini, G., & Quagliarini, E. (2021). Seismic risk of Open Spaces in Historic built Environments: A matrix-based approach for emergency management and disaster response. *International Journal of Disaster Risk Reduction, 65*, Article 102552. https://doi.org/10.1016/j.ijdrr.2021.102552

Bernal, G. A., Salgado-Gálvez, M. A., Zuloaga, D., Tristancho, J., González, D., & Cardona, O.-D. (2017). Integration of probabilistic and multi-hazard risk assessment within Urban development planning and Emergency preparedness and response: Application to Manizales, Colombia. *International Journal of Disaster Risk Science, 8*, 270–283. https://doi.org/10.1007/s13753-017-0135-8

Biondi, D., Scarcella, G. E., & Versace, P. (2023). CERCA (Cascading Effects in Risk Consequences Assessment): An operational tool for geo-hydrological scenario risk assessment and cascading effects evaluation. *Hydrology Research, 54*, 189–207. https://doi.org/10.2166/nh.2023.088

Booth, A., Chmutina, K., & Bosher, L. (2020). Protecting crowded places: Challenges and drivers to implementing protective security measures in the built environment. *Cities, 107*, Article 102891. https://doi.org/10.1016/j.cities.2020.102891

Bosina, E., & Weidmann, U. (2017). Estimating pedestrian speed using aggregated literature data. *Physica A: Statistical Mechanics and its Applications, 468*, 1–29. https://doi.org/10.1016/j.physa.2016.09.044

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

Cantatore, E., & Fatiguso, F. (2021). An energy-resilient retrofit methodology to climate change for historic districts. *Application in the mediterranean area. Sustain, 13*. https://doi.org/10.3390/su13031422

Cantatore, E., Quagliarini, E., & Fatiguso, F. (2022). 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*, Article 12301. https://doi.org/10.3390/su141912301

Cantatore, E., Esposito, D., & Sonnessa, A. (2023). Mapping the multi-vulnerabilities of outdoor places to enhance the resilience of historic urban districts: The case of the Apulian region exposed to slow and rapid-onset disasters. *Sustainability, 15*, Article 14248. https://doi.org/10.3390/su151914248

Cantatore, E., Quagliarini, E., & Fatiguso, F. (2024). Terrorism risk assessment for historic urban open areas. *Heritage, 7*, 5319–5355. https://doi.org/10.3390/heritage7100251

Cao, S., Qian, J., Li, X., & Ni, J. (2022). Evacuation simulation considering the heterogeneity of pedestrian under terrorist attacks. *International Journal of Disaster Risk Reduction, 79*, Article 103203. https://doi.org/10.1016/j.ijdrr.2022.103203

Cardone, B., D'Ambrosio, V., Di Martino, F., & Miraglia, V. (2024). Hierarchical fuzzy MCDA multi-risk model for detecting critical urban areas in climate scenarios. *Applied Sciences, 14*, 3066. https://doi.org/10.3390/app14073066

Carmona, M. (2021). *Public places urban spaces*. Routledge.

Castaño-Rosa, R., Pelsmakers, S., Järventausta, H., Poutanen, J., Tähtinen, L., Rashidfarokhi, A., & Toivonen, S. (2022). Resilience in the built environment: Key characteristics for solutions to multiple crises. *Sustainable Cities and Society, 87*, Article 104259. https://doi.org/10.1016/j.scs.2022.104259

Cheliotis, K. (2020). An agent-based model of public space use. *Computers, environment and urban systems, 81*, Article 101476. https://doi.org/10.1016/j.compenvurbsys.2020.101476

Chen, C., Zhao, D., He, F., & Sun, F. (2023). A comprehensive multi-hazard risk assessment model for an urban agglomeration with multiple factors. *Journal of Safety Science and Resilience, 4*, 43–51. https://doi.org/10.1016/j.jnlssr.2022.09.008

Cheung, P. K., & Jim, C. Y. (2019). Improved assessment of outdoor thermal comfort: 1-hour acceptable temperature range. *Building and environment, 151*, 303–317. https://doi.org/10.1016/j.buildenv.2019.01.057

Coaffee, J., O'Hare, P., & Hawkesworth, M. (2009). The visibility of (in) security: The aesthetics of planning urban defences against terrorism. *Security Dialogue, 40*, 489–511.

Crank, P. J., Sailor, D. J., Ban-Weiss, G., & Taleghani, M. (2018). Evaluating the ENVI-met microscale model for suitability in analysis of targeted urban heat mitigation strategies. *Urban Climate, 26*, 188–197. https://doi.org/10.1016/j.uclim.2018.09.002

Curt, C. (2021). Multirisk: What trends in recent works? – A bibliometric analysis. *Science of the Total Environment, 763*, Article 142951. https://doi.org/10.1016/j.scitotenv.2020.142951

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

D'Amico, A., Sparvoli, G., Bernardini, G., Bruno, S., Fatiguso, F., Currà, E., & Quagliarini, E. (2024). Behavioural-based risk of the Built Environment: Key performance indicators for sudden-onset disaster in urban open spaces. *International Journal of Disaster Risk Reduction, 103*, Article 104328. https://doi.org/10.1016/j.ijdrr.2024.104328

D'Orazio, M., Longhi, S., Olivetti, P., & Bernardini, G. (2015). Design and experimental evaluation of an interactive system for pre-movement time reduction in case of fire. *Automation in Construction, 52*, 16–28. https://doi.org/10.1016/j.autcon.2015.02.015

Dastjerdi, M. S., & Lak, A. (2023). Towards resilient place emphasizing urban form: An assessment framework in urban design. *Sustainable Cities and Society, 96*, Article 104646. https://doi.org/10.1016/j.scs.2023.104646

De Lotto, R., & Sturla, S. (2017). Measure and proportion as keyword for qualitative town squares. *Journal of Public Space, 2*, 69. https://doi.org/10.5204/jps.v2i1.51

de Ruiter, M. C., & van Loon, A. F. (2022). The challenges of dynamic vulnerability and how to assess it. *iScience, 25*, Article 104720. https://doi.org/10.1016/j.isci.2022.104720

Desai, S. (2017). Economic effects of terrorism: Local and city considerations, priorities for research and policy. *Geographical Compass, 11*. https://doi.org/10.1111/gec3.12332

Estacio, I., Hadfi, R., Blanco, A., Ito, T., & Babaan, J. (2022). Optimization of tree positioning to maximize walking in urban outdoor spaces: A modeling and simulation framework. *Sustainable Cities and Society, 86*, Article 104105. https://doi.org/10.1016/j.scs.2022.104105

Fahed, J., Kinab, E., Ginestet, S., & Adolphe, L. (2020). Impact of urban heat island mitigation measures on microclimate and pedestrian comfort in a dense urban district of Lebanon. *Sustainable Cities and Society, 61*, Article 102375. https://doi.org/10.1016/j.scs.2020.102375

Federal Emergency Management Agency (2007) FEMA 430: Site and Urban design for security: Guidance against potential terrorist attacks.

FEMA-426/BIPS-06 (2011) Reference manual to mitigate potential terrorist attacks against buildings. FEMA-426/BIPS-06 ed 2 510.

French, E. L., Birchall, S. J., Landman, K., & Brown, R. D. (2019). Designing public open space to support seismic resilience: A systematic review. *International Journal of Disaster Risk Reduction, 34*, 1–10. https://doi.org/10.1016/j.ijdrr.2018.11.001

Gómez Zapata, J. C., Pittore, M., Brinckmann, N., Lizarazo-Marriaga, J., Medina, S., Tarque, N., & Cotton, F. (2023). Scenario-based multi-risk assessment from existing single-hazard vulnerability models. An application to consecutive earthquakes and tsunamis in Lima, Peru. *Natural Hazards and Earth System Sciences, 23*, 2203–2228. https://doi.org/10.5194/nhess-23-2203-2023

Galderisi, A., & Limongi, G. (2021). A comprehensive assessment of exposure and vulnerabilities in multi-hazard urban environments: A key tool for risk-informed planning strategies. *Sustainability, 13*, 9055. https://doi.org/10.3390/su13169055

Gandini, A., Quesada, L., Prieto, I., & Garmendia, L. (2021). Climate change risk assessment: A holistic multi-stakeholder methodology for the sustainable development of cities. *Sustainable Cities and Society, 65*. https://doi.org/10.1016/j.scs.2020.102641

Gherri, B., Maiullari, D., Finizza, C., Maretto, M., & Naboni, E. (2021). On the thermal resilience of Venetian open spaces. *Heritage, 4*, 4286–4303. https://doi.org/10.3390/heritage4040236

Goepel K.D. (2013) Implementing the analytic hierarchy process as a standard method for multi-criteria decision making in corporate enterprises – a new AHP Excel template with multiple inputs.

Grissom, T. V, McIlhatton, D., DeLisle, J. R., & Hardy, M. (2019). Decision-theoretic behavioral analytics: Risk management and terrorist intensity. *Behavioral Sciences of Terrorism and Political Aggression, 11*, 73–112. https://doi.org/10.1080/19434472.2018.1551917

Gupta H, Sen, Adluri, T., Sanderson, D., González, A. D., Nicholson, C. D., & Cox, D. (2024). Multi-objective optimization of mitigation strategies for buildings subject to multiple hazards. *International Journal of Disaster Risk Reduction, 100*, Article 104125. https://doi.org/10.1016/j.ijdrr.2023.104125

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

Han, S., Song, D., Xu, L., Ye, Y., Yan, S., Shi, F., Zhang, Y., Liu, X., & Du, H. (2022b). Behaviour in public open spaces: A systematic review of studies with quantitative research methods. *Building and environment, 223*, Article 109444. https://doi.org/10.1016/j.buildenv.2022.109444

Hochrainer-Stigler, S., Šakić Trogrlić, R., Reiter, K., Ward, P. J., de Ruiter, M. C., Duncan, M. J., Torresan, S., Ciurean, R., Mysiak, J., Stuparu, D., & Gottardo, S. (2023). Toward a framework for systemic multi-hazard and multi-risk assessment and management. *iScience, 26*, Article 106736. https://doi.org/10.1016/j.isci.2023.106736

Intergovernmental Panel on Climate Change (IPCC). (2023). *Climate change 2022 – impacts, adaptation and vulnerability. contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change*. New York, New York, USA: Cambridge University Press.

Jato-Espino, D., Manchado, C., & Roldán-Valcarce, A. (2025). A compact multi-hazard assessment model to identify urban areas prone to heat islands, floods and particulate matter. *International Journal of Disaster Risk Reduction, 119*, Article 105277. https://doi.org/10.1016/j.ijdrr.2025.105277

Julià, P. B., & Ferreira, T. M. (2021). From single- to multi-hazard vulnerability and risk in historic Urban Areas: A literature review. *Natural Hazards, 108*, 93–128. https://doi.org/10.1007/s11069-021-04734-5

Kalvach Z. (2016) Basics of soft targets protection–guidelines.

Komendantova, N., Mrzyglocki, R., Mignan, A., Khazai, B., Wenzel, F., Patt, A., & Fleming, K. (2014). Multi-hazard and multi-risk decision-support tools as a part of participatory risk governance: Feedback from civil protection stakeholders. *International Journal of Disaster Risk Reduction, 8*, 50–67. https://doi.org/10.1016/j.ijdrr.2013.12.006

Laino, E., Toledo, I., Aragonés, L., & Iglesias, G. (2024). A novel multi-hazard risk assessment framework for coastal cities under climate change. *Science of The Total Environment, 954*, Article 176638. https://doi.org/10.1016/j.scitotenv.2024.176638

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

Li, S., Zhuang, J., & Shen, S. (2017). A three-stage evacuation decision-making and behavior model for the onset of an attack. *Transportation research. Part C, Emerging technologies, 79*, 119–135. https://doi.org/10.1016/j.trc.2017.03.008

Li, H., Wang, Z., & Hong, T. (2021). Occupant-centric key performance indicators to inform building design and operations. *Journal of Building Performance Simulation, 14*, 814–842. https://doi.org/10.1080/19401493.2021.1876771

Li, N., Guo, Z., Geng, W., Li, L., & Li, Z. (2023). Design strategies for renovation of public space in Beijing's traditional communities based on measured microclimate and thermal comfort. *Sustainable Cities and Society, 99*, Article 104927. https://doi.org/10.1016/j.scs.2023.104927

Liang, Z., Huang, J., Wang, Y., Wei, F., Wu, S., Jiang, H., Zhang, X., & Li, S. (2021). The mediating effect of air pollution in the impacts of urban form on nighttime urban heat island intensity. *Sustainable Cities and Society, 74*, Article 102985. https://doi.org/10.1016/j.scs.2021.102985

Lu, P., Zhang, Z., Li, M., Chen, D., & Yang, H. (2020). Agent-based modeling and simulations of terrorist attacks combined with stampedes. *Knowledge-Based System, 205*, Article 106291. https://doi.org/10.1016/j.knosys.2020.106291

Martinelli, A., Carlucci, F., & Fiorito, F. (2024). On the role of the building envelope on the urban heat island mitigation and building energy performance in Mediterranean cities: A case study in southern Italy. *Climate, 12*, 113. https://doi.org/10.3390/cli12080113

Mascheri, G., Chieffo, N., Arrighi, C., Del Gaudio, C., & Lourenço, P. B. (2024). A framework for multi-risk assessment in a historical area of Lisbon. *International Journal of Disaster Risk Reduction, 108*, Article 104508. https://doi.org/10.1016/j.ijdrr.2024.104508

Ministry of Interior (Italy) (2020) DM 03/08/2015: Technical fire prevention standards (testo coordinato dell'allegato I del DM 3 agosto 2015 - codice di prevenzione incendi - release beta 3).

Ouyang, M., Cheng, Z., Ma, J., Wang, H., & Mitoulis, S. A. (2024). Coupled urban risks: A complex systems perspective with a people-centric focus. *Engineering*. https://doi.org/10.1016/j.eng.2024.12.023

Pal, I., Kumar, A., & Mukhopadhyay, A. (2023). Risks to coastal critical infrastructure from climate change. *Annual review of environment and resources, 48*, 681–712. https://doi.org/10.1146/annurev-environ-112320-101903

Park, S., Tuller, S. E., & Jo, M. (2014). Application of Universal Thermal Climate Index (UTCI) for microclimatic analysis in urban thermal environments. *Landscape and Urban Planning, 125*, 146–155. https://doi.org/10.1016/j.landurbplan.2014.02.014

Pescaroli, G., & Alexander, D. (2017). Cross-sectoral and multi-risk approach to cascading disasters. *United nations office for disaster risk reduction (ed) words into action guidelines: National disaster risk assessment*. United Nations Office for Disaster Risk Reduction.

Pizzorni, M., Innocenti, A., & Tollin, N. (2024). Droughts and floods in a changing climate and implications for multi-hazard urban planning: A review. *City and Environment Interaction, 24*, Article 100169. https://doi.org/10.1016/j.cacint.2024.100169

Polese, M., Tocchi, G., Babič, A., Dolšek, M., Faravelli, M., Quaroni, D., Borzi, B., Rebora, N., Ottonelli, D., Wernhart, S., Pejovic, J., Serdar, N., Lebar, K., Rusjan, S., Masi, R., Resch, C., Kern, H., Cipranić, I., Ostojic, M., & Prota, A. (2024). Multi-risk assessment in transboundary areas: A framework for harmonized evaluation considering seismic and flood risks. *International Journal of Disaster Risk Reduction, 101*, Article 104275. https://doi.org/10.1016/j.ijdrr.2024.104275

Poljanšek, K., Marin Ferrer, M., De Groeve, T., & Clark, I. (2017). *Science for disaster risk management 2017: Knowing better and losing less*. Luxembourg: EUR 28034 EN, Publications Office of the European Union.

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

Quagliarini, E., Bernardini, G., & D'Orazio, M. (2023b). 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*, 5151–5188. https://doi.org/10.3390/heritage6070274

Quesada-Ganuza, L., Garmendia, L., Alvarez, I., & Roji, E. (2023). Vulnerability assessment and categorization against heat waves for the Bilbao historic area. *Sustainable Cities and Society, 98*, Article 104805. https://doi.org/10.1016/j.scs.2023.104805

Rosso, F., Bernabei, L., Bernardini, G., Cadena, J. D. B., Russo, M., D'Amico, A., Salvalai, G., Currà, E., Quagliarini, E., & Mochi, G. (2023). Mitigating multi-risks in the historical built environment: A multi-strategy adaptive approach. In J. Littlewood, R. J. Howlett, & L. C. Jain (Eds.), *Sustainability in energy and buildings 2022 . SEB 2022. smart innovation, systems and technologies* (pp. 197–207). Singapore: Springer. vol 336.

Rus, K., Kilar, V., & Koren, D. (2018). Resilience assessment of complex urban systems to natural disasters: A new literature review. *International Journal of Disaster Risk Reduction, 31*, 311–330. https://doi.org/10.1016/j.ijdrr.2018.05.015

Sáenz de Tejada, C., Daher, C., Hidalgo, L., Netanyahu, S., Nieuwenhuijsen, M., & Braubach, M. (2024). Urban planning, design and management approaches to building urban resilience: A rapid review of the evidence. *Cities Health, 8*, 932–955. https://doi.org/10.1080/23748834.2024.2364491

Salvalai, G., Blanco Cadena, J. D., Sparvoli, G., Bernardini, G., & Quagliarini, E. (2022). Pedestrian single and multi-risk assessment to SLODs in Urban built environment: A mesoscale approach. *Sustainability, 14*, Article 11233. https://doi.org/10.3390/su141811233

Salvati, A., Monti, P., Coch Roura, H., & Cecere, C. (2019). Climatic performance of urban textures: Analysis tools for a Mediterranean urban context. *Energy and buildings, 185*, 162–179. https://doi.org/10.1016/j.enbuild.2018.12.024

Sangiorgio, V., Bruno, S., & Fiorito, F. (2022). Comparative analysis and mitigation strategy for the urban heat island intensity in Bari (Italy) and in other six European cities. *Climate, 10*, 177. https://doi.org/10.3390/cli10110177

Schlumberger, J., Haasnoot, M., Aerts, J., & de Ruiter, M. (2022). Proposing DAPP-MR as a disaster risk management pathways framework for complex, dynamic multi-risk. *iScience, 25*, Article 105219. https://doi.org/10.1016/j.isci.2022.105219

Senanayake, G. P. D. P., Kieu, M., Zou, Y., & Dirks, K. (2024). Agent-based simulation for pedestrian evacuation: A systematic literature review. *International Journal of Disaster Risk Reduction, 111*, Article 104705. https://doi.org/10.1016/j.ijdrr.2024.104705

Sharifi, A. (2019). Resilient urban forms: A review of literature on streets and street networks. *Building and environment, 147*, 171–187. https://doi.org/10.1016/j.buildenv.2018.09.040

Song, Y., Liu, B., Li, L., & Liu, J. (2022). Modelling and simulation of crowd evacuation in terrorist attacks. *Kybernetes*. https://doi.org/10.1108/K-02-2022-0260

The European Commission (2022) Security by design: Protection of public spaces from terrorist attacks.

The United Nations Office for Disaster Risk Reduction (UNISDR) (2017) National disaster risk assessment. Geneva.

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

UNDRR (2016) A/RES/71/644 report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction.

US department of Homeland Security (2018) Planning considerations: Complex coordinated terrorist attacks.

van der Wal, C. N., Formolo, D., Robinson, M. A., Minkov, M., & Bosse, T. (2017). Simulating crowd evacuation with socio-cultural, cognitive, and emotional elements. *Lect Notes Comput Sci (including Subser Lect Notes Artif Intell Lect Notes Bioinformatics) 10480 LNCS*, 139–177. https://doi.org/10.1007/978-3-319-70647-4_11

Vanos, J. K., Middel, A., Poletti, M. N., & Selover, N. J. (2018). Evaluating the impact of solar radiation on pediatric heat balance within enclosed, hot vehicles. *Temperature, 5*, 276–292. https://doi.org/10.1080/23328940.2018.1468205

Verstockt, S., Van Hoecke, S., Tilley, N., Merci, B., Sette, B., Lambert, P., Hollemeersch, C.-F. J., & Van de Walle, R. (2011). FireCube: A multi-view localization framework for 3D fire analysis. *Fire safety journal, 46*, 262–275. https://doi.org/10.1016/j.firesaf.2011.03.001

Walls, W., Parker, N., & Walliss, J. (2015). Designing with thermal comfort indices in outdoor sites. *Living and Learning: Research for a Better Built Environment*, 1117–1128.

Wilensky U. (1999) NetLogo. http://ccl.northwestern.edu/netlogo/. In: Cent. Connect. Learn. Comput. Model. Northwest. Univ. Evanston.

Yu, W., Zhu, J., Zhou, W., & Wang, W. (2024). Spatial heterogeneity of the integrated risks of urban heat stress and flooding strike. *Science of The Total Environment, 954*, Article 176517. https://doi.org/10.1016/j.scitotenv.2024.176517

Zhang, N., Huang, H., Su, B., & Zhao, J. (2015). Analysis of dynamic road risk for pedestrian evacuation. *Physica A: Statistical Mechanics and its Applications, 430*, 171–183. https://doi.org/10.1016/j.physa.2015.02.082

Zhao, Z., Li, J., & Fu, Z. (2024). Study on summer microclimate analysis and optimization strategies for urban parks in Xinjiang—A case Study of Mingzhu Park. *Sustainability, 16*, 7687. https://doi.org/10.3390/su16177687

Zhu, R., Lucas, G. M., Becerik-Gerber, B., & Southers, E. G. (2020). Building preparedness in response to active shooter incidents: Results of focus group interviews. *International Journal of Disaster Risk Reduction, 48*, Article 101617. https://doi.org/10.1016/j.ijdrr.2020.101617