WP4–Human factors simulation in BETs and definition of a related behavioral-based (B-based) resilience metric

T4.2 Simulators application to selected BETs in their current state and by applying current SUOD/SLOD standards mitigation strategies. Interferences assessment between selected SUOD/SLOD through simulation-based approach, with possible overlap of effects and related amplifications. Definition of a set of KPIs for overall resilience evaluation of BE and criteria for their correlation

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Abstract

The development of single and multi-risk metrics is founded on the combination between the specific key performance indicators (KPIs) that could be relevant for each of the investigated condition. As a result, the final metrics could support the designers since they can summarize the overall scenario conditions by a single indicator, in which each factor is weighted according to its impact on the final outcomes. In this sense, indicators should also comprise the description of human behaviours in SUOD and SLOD emergencies, in view of their impact on the overall resilience, as shown in WP1, WP2 and WP4 activities of the project. This work offers single and multi-risk metrics for the built environment (BE) resilience, which have been developed according to an analytical hierarchy process (AHP) approach. First, AHP has been defined for each single risk, by involving the KPIs derived from D4.2.2 and D4.2.3. Each AHP has been performed by a partner of the research group according to its expertise (in relation to WP1 and WP2 leading actions). Then, for SUODs, group judgments have been provided by collecting the single partner results and merging them. The AHP consensus indicator has been also calculated for each single risk metrics, so as to define the convergence between the assessed priorities of each KPI. Results provide specific metrics ranging from 0 to 1, which can be used to quickly compare different conditions in the BE (and in the BE typologies), to be also applied in WP5-D5.2.1 and WP6-D6.2.3 activities.

Keywords

Analytical hierarchy process; human behaviour; risk assessment; key performance indicators; risk metrics; single risk; multi-risk

Approvals

Role	Name	Partner
Coordinator	Enrico Quagliarini	UNIVPM
Task leader	Enrico Quagliarini	UNIVPM

Revision versions

Revision	Date	Short summary of modifications	Name	Partner
0.1	12.09.2022	AHP integration methodology	Gabriele Bernardini	UNIVPM
0.2	29.11.2022	AHP revision results and results revisions depending on simulation updates	Gabriele Bernardini	UNIVPM
0.3	22.06.2023	Figures editing, proofread and consistency check also in respect to published works (i.e. Cadena et al. 2023)	Gessica Sparvoli	UNIVPM

Summary

1. Introduction

The risk and resilience assessment of the Built Environment (BE) could be supported by Key performance indicators (KPIs) oriented to understand the interaction between the BE users and the BE in emergency conditions (Marzouk and Mohamed 2019; Li et al. 2021; Bernardini and Ferreira 2022). Previous activities on D4.2.2 and D4.2.3 supported the development of general KPIs relating to Sudden Onset disasters (SUODs), i.e. seismic emergency and terrorist acts, and Slow Onset disasters (SLODs), i.e. air pollution and increasing temperature. Anyway, these indicators sparsely describe the risk level in the BE and of the BE, and unique metrics should be encouraged to offer a rapid overview of the overall risk level (Haimes 2012; León et al. 2021). Such metrics could explore risk level, at least, for each assessed risk, but could be also employed towards multi-risk assessment, including using a coupled events perspective (Curt 2021).

Previous works underlined the rule of multi criteria decision making solutions in the development of overall judgement approaches, and, so, of metrics (Prawiranegara 2014; Fadlalla et al. 2015; Quagliarini et al. 2018; Drakaki et al. 2018; Yao et al. 2021). In this general context, the Analytical Hierarchy Process (AHP) surely represents one of the most interesting approaches (Saaty 1980), since it allows to supervise the assessment process by decision makers in a structured manner. The method allows to define priorities to each factor in the assessment process, by verifying the consistency of the result through specific indexes (Goepel 2013). This approach could be easily adopted also in case of decision groups, in which the importance of the assessment could be stated, first, at the individual level, and then a the whole group level, as an aggregation of the individual responses (Dong et al. 2010; Goepel 2013).

Starting from the AHP capabilities, this work applies this kind of multi decision criteria making approach to develop a metric for risk assessment in the BE. KPIs developed in D4.2.2, in particular, have been collected and compared, thus deriving a unique metric which combines both the SLODs (air pollution and increasing temperature), one for seismic risk and one for terrorist risk. In fact, the base assumption is that the final metrics will divide SLODs and SUODs risk assessment since SLODs are used to populate the scenario and SUODs are considered in evacuation conditions. Thus, SLODs and SUODs are considered as not contemporary. SUODs are separated due to their specific features and the emergency phenomena (i.e. leaving versus entering the BET), according to D4.1 (i.e. see Section 2). SLODs are combined since they are concurrent at the same time in the BET (Salvalai et al. 2022).

These metrics thus include behavioural issues since the KPIs consider the correlation between the users' response to the event and the BE and emergency features, also relying on simulation results.

2. Methodology and phases

The work is organized in three main activities for metrics definition. Nevertheless, the development of all the metrics still exploits the application of the AHP approach according to the feature of each risk, by using the KPIs for SLODs from D4.2.3 and for SUODs from D4.2.2 as inputs for the final metrics. As a result, the whole ranking of a BE/BET could be reached as the summary of the risk metrics.
The first activity concerns the SUODs metrics development. This first phase of this activity allowed to provide priorities for each KPIs to each of the partners in the group, thus providing a single-partner specific metric (see Section 2.1). The second phase concerns the aggregation of these AHP results so as to derive group priorities, verifying the consensus between the participants (see Section 2.2). Figure 1 shows the general workflow of these research steps.
The second activity concerns the SLODs metric development. In this case, we have a single phase (Section 2.3) which relates to the AHP process to combine KPIs on increasing temperature and pollution effects. For

both the activities, the final risk metrics are the offered within the results in respect of the original BET conditions, to test their effectiveness and capabilities in comparing and contrasting the BET-related scenarios. Such results are based on D4.2.2 and D4.2.3 results on the KPIs.

The last activity concerns the definition of a unique risk multidimensional vector which merges the SLODs and SUODs metrics (Section 2.4).

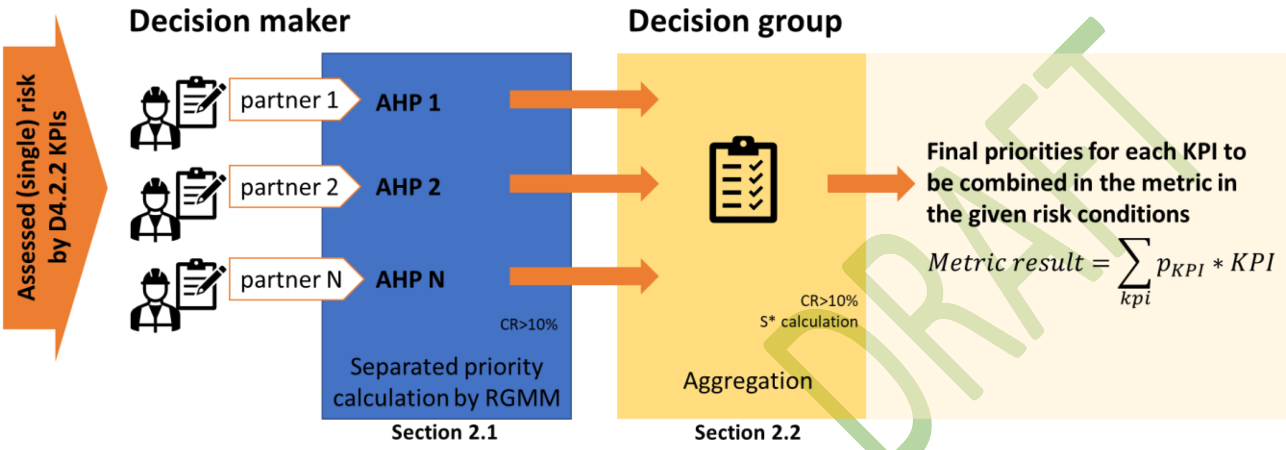

Figure 1. General workflow from the single decision maker's AHP to the decision group making, by including references to the related sections where methods are explained.

2.1 AHP for SUODs

The AHP approach (Saaty 1980; Goepel 2013) has been selected to provide priorities to each of the KPIs defined in D4.2.2, in a single risk approach. This means that KPIs have been considered in a separated manner for terrorist risk and for seismic risk, as shown in D4.2.2. A pair-wise comparison between the KPIs has been firstly performed, using a linear integer scale ranging from 1 (same importance) to 9 (maximum importance of the considered KPI in respect to the other) (Saaty 1980). The comparisons were performed by considering a single layer, thus comparing all the related KPIs together. In particular, Table 1 shows the KPIs list for seismic risk (10 KPIs) and terrorist risk (11 KPIs). Then, priorities pi are calculated using the row geometric mean method (RGMM) (Goepel 2013), considering that the sum of these priorities in the metrics is equal to one for each assessed single risk.

Table 1. List of the KPIs for seismic risk and terrorist risk AHPs.

KPI ID	Seismic risk	Terrorist acts risk
1	Balance index of debris	-
2	Road resistor coefficient	Road resistor coefficient
3	Pedestrian speed conservation	Pedestrian speed conservation
4	Obstacle friction rate	Obstacle friction rate
5	Temporary secure Open Spaces	Temporary secure Open Spaces
6	Exposure index	Exposure index
7	Normalized Evacuation time percentile	Normalized Evacuation time percentile
8	Crowd effects	Crowd effects
9	Mean flow rate at the exit	Mean flow rate at the exit
10	Number of Evacuees for SUOD	Number of Evacuees for SUOD

11	-	Number of deaths / casualties
12	-	Obstacle protection rate

The process has been supervised by calculating the Consistency Ratio (CR), which should be lower than 10% to confirm the acceptability of the proposed priorities. The final metric outputs will then vary between zero (minimum risk) and one (maximum risk), without requiring further normalization to compare different scenarios.

The AHP has been performed by each partner of the research group, depending on its skills according to WP1 and WP2 activities. Thus, BA and PM provided AHP for terrorist risk (thus having a total number of 2 assessment matrixes), while RM, PG and PM provided AHP for seismic risk (thus having a total number of 3 assessment matrixes).

2.2 Group decision making for SUODs and final metrics criteria

The AHP matrices derived from each partner (considered in the following as a decision maker) have been collected. The comparison matrix A is based on the aggregation of individual judgments and using the same RGMM as the selected prioritization method (Dong et al. 2010; Goepel 2013). The methodology proposed in (Goepel 2013) has been used to evaluate the inconsistencies (and so the CR) and the AHP consensus indicator. Concerning inconsistency, the CR for the aggregated priorities is calculated, by verifying that CR<10% as in the process in Section 2.1 Then, the AHP consensus indicator S* is calculated to verify its percentage values. S* is then an homogeneity index based on the Shannon entropy (Goepel 2013). When S* is close to 0%, there is no consensus between the decision makers, while when S* is close to 100%, the decision makers' results fully agree. Thus, higher S* values would imply higher consensus of the single decision makers involved in the AHP assessment.

Thanks to the adoption of a single comparison layer, the final metric output for a given risk will be equal to the sum of the multiplication between each KPI aggregation-based priority and the related KPI value (Saaty 1980; Dong et al. 2010; Goepel 2013), as also shown in Figure 1.

2.3 AHP and metrics development for SLODs

The AHP approach has been chosen to combine the two indicators of SLODs risk, increasing temperature and air pollution, which have been derived from D4.2.3.
In particular, effects on increasing temperature on users (and thus their risk) have been computed according to D4.2.3, Section 2 (please also compare (Cadena et al. 2023)) considering the potential sweating rate. Therefore, the amount of water loss ($WL\%_{age}$ [%]) has been calculated based on the sweating rate associated with a UTCI-heatwaves category. Individual physiological conditions for the specific water loss risk are assessed depending on age classes (Salvalai et al. 2022; Cadena et al. 2023): toddlers (TU), children (PC), young adults (YA), adults (AU), elderly (EU).
The same AHP approach (introduced in Section 2.1) has been also used to provide a priority for each age class defined in D3.2.3, and following the method and criteria proposed in (Salvalai et al. 2022). The result of the process led to the definition of the following weights ($K_{WLN,\ age}$ [-]), characterized by CR=5.5%<10%, thus confirming the acceptability of the comparisons made. The weights are: TU=41.0%, PC=17.4%, YA=8.5%, AU=3.1%, EU=30.1%.
To obtain a single final indicator for increasing temperature risk (RWLn [-]) varying between 0 (lowest risk) and 1 (highest risk), the normalized percent water loss (WLn_{age} [%] has been multiplyed by the individual values by their aforementioned AHP-derived weights ($K_{WLn,age}$) as in Equation 1.

Equation 1

$$RWLn = \frac{\sum_{age=TU}^{EU} K_{W\,Ln,age} * WLn_{age}}{100}$$

Specifically, the normalized percent water loss (WLn_{age}) has been calculated as a critical value and not acceptable beyond, 4% water loss relative to body weight (Equation 2). Previous work has defined this threshold for initial symptoms of dehydration, which can be considered critical for the users' safety (Bröde et al. 2009; Cadena et al. 2023).

Equation 2

$$WLn_{age} = \max\left(100, \frac{WL\%_{age}}{4\%} * 100\right) [\%]$$

For air pollution risk, the indicator consists of two parameters, according to the same insights of D4.2.3, Section 3 (also compare (Cadena et al. 2023)). The *Hospital admission with cardiovascular issues* and the *mortality* are considered as air pollution effects for the users, and they are computed by assigning each the same weight to obtain the final metric. Thus, the same level of hazard to the health of users for these two phenomena are considered. In fact, being the two parameters equally hazardous to users' health (Salvalai et al. 2022) and thus it has not been possible to determine the priority of one over the other.
The data to obtain the indicators are assessed considering one unique climate scenario to test the methodological approach and to compare effects on SLODs stress and users' behaviors. In detail, the climate of Milan, Italy is analyzed for both UTCI and AQI as it can suffer critical simultaneous SLODs (Cadena et al. 2023).
Finally, the two risks are analyzed from two additional behavioral categories, *1-hour behavior (HW1-h and AP1-h)* and *transient behavior (HWt and APt)*, according to D4.2.3 Section 3 (also compare (Cadena et al. 2023)). To combine the effects on the two typologies of users in respect to the fruition time in the BET, the aforementioned indicators are combined considering the same impact on the final metric through using Equation 3.

Equation 3

$$RI_{SLODs} = (HW_{1-h} * 0.25) + (HW_t * 0.25) + (AP_{1-h} * 0.25) + (AP_t * 0.25)$$

2.4 Multidimensional vector for multi-risk assessment

The metrics have been organized to obtain four related single risk vectors and then they are merged into a unique multi-risk metrics which relies on a multidimensional vector standpoint. This final activity aims at facilitating the comparison of BETs according to the pursued multirisk approach. To this end, an aggregation of data between the BET layout configurations have been performed too.

To this end, two three-dimensional vectors are defined for the two SUOD risks that summarize the three scenarios that compose the metrics, the base scenario Sb, the risk scenario 1 (SE1 and ST1), and the risk scenario 2 (SE2 and ST2), in a single module through Equation 4.

Equation 4

$$SE(T) = \sqrt{\frac{SbE(T)^2 + SE(T)1^2 + SE(T)2^2}{3}}$$

Equation 5, on the contrary, shows the two assumed SLODs metrics which merges the effects of heatwaves (SH) and air pollution (SP) on the users according to the combination of transient and 1-hour behaviours. According to a conservative approach, each of these behaviours have been considered having the same impact on the final metric.

Equation 5

$$SH = 0.5\, HW_t + 0.5\, HW_{1-h}\ ;\ SP = 0.5\, AP_t + 0.5\, AP_{1-h}$$

The outcomes of Equation 4 and Equation 5 have been processed according to statistical analysis, to derive median values of related single risk metrics, for each BET. Values over the median value imply that the BET is more susceptible that the others to the specific single risk. A comparison with D3.2.1-based definition of risks depending on the BET features, as published in (D'Amico et al. 2021), has been performed to evaluate differences among theoretical and simulation-based susceptibility to risks.

Finally, SE, ST, SH and SP are then combined in a multirisk vector, which modules is calculated according to Equation 6. This combination represents the worst possible scenario, one in which all risks are overlapped. As for the previous metrics, a conservative approach has been selected, by considering that all the risks have the same impact on the final multirisk condition.

Equation 6

$$S_{TOT} = \sqrt{\frac{SE^2 + ST^2 + SH^2 + SP^2}{4}}$$

3. Results and discussion

3.1 SUODs metrics results

Figure 2 shows the AHP matrices for seismic risk, thus relating to the PG, PM and RM AHP, and, finally, the aggregated matrix, by also including the related CR for each of them and the priorities. In general terms, all the decision makers' AHP as well as the aggregation are characterized by CR<10%, thus confirming the acceptability of the pair-wise comparisons. Figure 3 graphically compares the outcoming priorities, thus underlining main differences between the decision makers. In general terms, main differences in the priorities are due to crowd effects, balance index if debris, number of evacuees, thus underlining that each decision maker could assign different impacts to behavioral-based phenomena according to the related core of expertise. As a consequence, the S*=48% thus confirming an average consensus between the single decision makers. The sample dimension could impact the final S* result.

KPI		KPI										priority
	Decision maker: PG	1	2	3	4	5	6	7	8	9	10	
1	Balance index of debris	1,000	5,000	5,000	4,000	1,000	2,000	4,000	5,000	4,000	4,000	**0,221**
2	Road resistor coefficient	0,200	1,000	3,000	2,000	0,250	0,250	5,000	4,000	3,000	0,500	**0,079**
3	Pedestrian speed conservation	0,200	0,333	1,000	0,500	0,167	0,200	0,500	3,000	0,500	0,167	**0,030**
4	Obstacle friction rate	0,250	0,500	2,000	1,000	0,333	0,333	3,000	4,000	3,000	1,000	**0,073**
5	Temporary secure OSs	1,000	4,000	6,000	3,000	1,000	3,000	5,000	6,000	5,000	5,000	**0,243**
6	Exposure index	0,500	4,000	5,000	3,000	0,333	1,000	5,000	5,000	5,000	4,000	**0,172**
7	Evacuation time percentile	0,250	0,200	2,000	0,333	0,200	0,200	1,000	0,333	1,000	0,250	**0,029**
8	Crowd effects	0,200	0,250	0,333	0,250	0,167	0,200	3,000	1,000	4,000	0,333	**0,035**
9	Mean flow rate at the exit	0,250	0,333	2,000	0,333	0,200	0,200	1,000	0,250	1,000	0,333	**0,031**
10	Number of Evacuees for SUOD	0,250	2,000	6,000	1,000	0,200	0,250	4,000	3,000	3,000	1,000	**0,087**
	CR=7,62%											

	Decision maker: PM	1	2	3	4	5	6	7	8	9	10	
1	Balance index of debris	1,000	1,000	6,000	4,000	0,250	0,250	5,000	0,500	5,000	0,500	**0,090**
2	Road resistor coefficient	1,000	1,000	5,000	3,000	0,250	0,333	6,000	0,500	5,000	0,500	**0,090**
3	Pedestrian speed conservation	0,167	0,200	1,000	0,333	0,200	0,167	0,500	0,200	0,333	0,167	**0,019**
4	Obstacle friction rate	0,250	0,333	3,000	1,000	0,200	0,200	3,000	1,000	3,000	0,200	**0,048**
5	Temporary secure OSs	4,000	4,000	5,000	5,000	1,000	0,333	5,000	3,000	5,000	5,000	**0,212**
6	Exposure index	4,000	3,000	6,000	5,000	3,000	1,000	6,000	3,000	6,000	3,000	**0,258**
7	Evacuation time percentile	0,200	0,167	2,000	0,333	0,200	0,167	1,000	0,333	1,000	0,200	**0,027**
8	Crowd effects	2,000	2,000	5,000	1,000	0,333	0,333	3,000	1,000	5,000	0,500	**0,095**
9	Mean flow rate at the exit	0,200	0,200	3,000	0,333	0,200	0,167	1,000	0,200	1,000	0,167	**0,026**
10	Number of Evacuees for SUOD	2,000	2,000	6,000	5,000	0,200	0,333	5,000	2,000	6,000	1,000	**0,133**
	CR=9,28%											

	Decision maker: RM	1	2	3	4	5	6	7	8	9	10	
1	Balance index of debris	1,000	3,000	5,000	3,000	1,000	1,000	5,000	7,000	5,000	7,000	**0,211**
2	Road resistor coefficient	0,333	1,000	3,000	1,000	0,333	0,333	3,000	5,000	3,000	5,000	**0,098**
3	Pedestrian speed conservation	0,200	0,333	1,000	0,333	0,200	0,200	1,000	3,000	1,000	3,000	**0,044**
4	Obstacle friction rate	0,333	1,000	3,000	1,000	0,333	0,333	3,000	5,000	3,000	5,000	**0,098**
5	Temporary secure OSs	1,000	3,000	5,000	3,000	1,000	1,000	5,000	7,000	5,000	7,000	**0,211**
6	Exposure index	1,000	3,000	5,000	3,000	1,000	1,000	5,000	7,000	5,000	7,000	**0,211**
7	Evacuation time percentile	0,200	0,333	1,000	0,333	0,200	0,200	1,000	3,000	1,000	3,000	**0,044**
8	Crowd effects	0,143	0,200	0,333	0,200	0,143	0,143	0,333	1,000	0,333	1,000	**0,021**
9	Mean flow rate at the exit	0,200	0,333	1,000	0,333	0,200	0,200	1,000	3,000	1,000	3,000	**0,044**
10	Number of Evacuees for SUOD	0,143	0,200	0,333	0,200	0,143	0,143	0,333	1,000	0,333	1,000	**0,021**
	CR=1,95%											

	AGGREGATION	1	2	3	4	5	6	7	8	9	10	
1	Balance index of debris	1,000	2,466	5,313	3,634	0,630	0,794	4,642	2,596	4,642	2,410	**0,170**
2	Road resistor coefficient	0,405	1,000	3,557	1,817	0,275	0,303	4,481	2,154	3,557	1,077	**0,093**
3	Pedestrian speed conservation	0,188	0,281	1,000	0,382	0,188	0,188	0,630	1,216	0,550	0,437	**0,031**
4	Obstacle friction rate	0,275	0,550	2,621	1,000	0,281	0,281	3,000	2,714	3,000	1,000	**0,074**
5	Temporary secure OSs	1,587	3,634	5,313	3,557	1,000	1,000	5,000	5,013	5,000	5,593	**0,233**
6	Exposure index	1,260	3,302	5,313	3,557	1,000	1,000	5,313	4,718	5,313	4,380	**0,222**
7	Evacuation time percentile	0,215	0,223	1,587	0,333	0,200	0,188	1,000	0,693	1,000	0,531	**0,034**
8	Crowd effects	0,385	0,464	0,822	0,368	0,199	0,212	1,442	1,000	1,882	0,550	**0,043**
9	Mean flow rate at the exit	0,215	0,281	1,817	0,333	0,200	0,188	1,000	0,531	1,000	0,550	**0,035**
10	Number of Evacuees for SUOD	0,415	0,928	2,289	1,000	0,179	0,228	1,882	1,817	1,817	1,000	**0,065**
	CR=2,37%											

Figure 2. AHP matrices per seismic risk: single decision makers and final aggregation results, including priority of the related KPIs (on the last column on the right) and CR values.

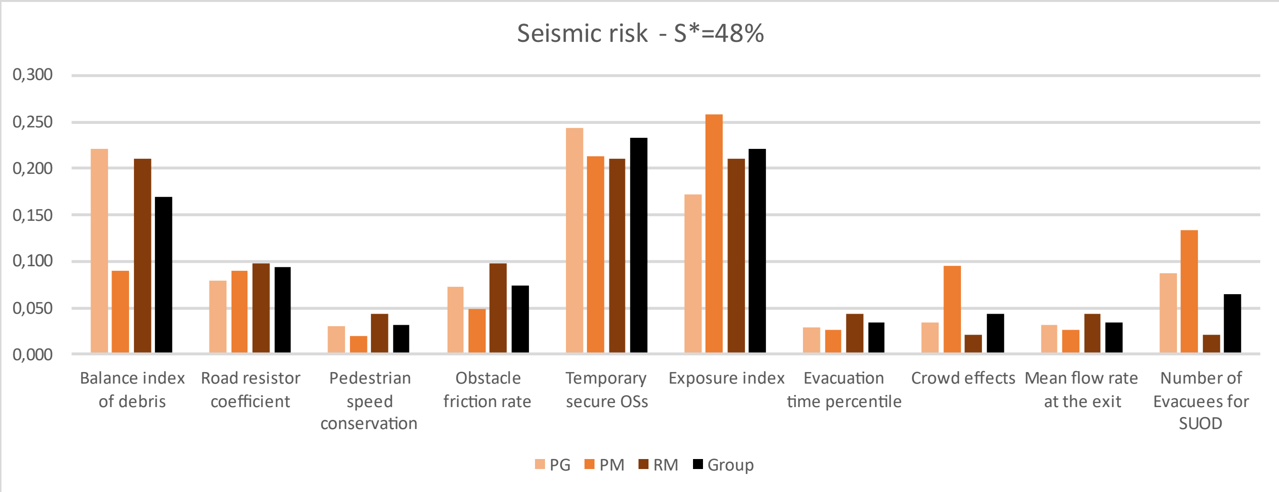

Figure 3. Priority weights for the single decision makers and for the group aggregation for seismic risk.

Figure 4 shows the AHP matrices for terrorist risk, thus relating to the BA and PM AHP, and, finally, the aggregated matrix, by also including the related CR for each of them and the priorities. In general terms, all the decision makers' AHP as well as the aggregation are characterized by CR<10%, thus confirming the acceptability of the pair-wise comparisons. Figure 5 graphically compares the outcoming priorities, thus underlining main differences between the decision makers. In general terms, the consensus is a bit lower than the one of seismic risk AHP, as confirmed by S*=42%, thus confirming a moderate consensus between the two decision makers. In this sense, the number of decision makers impacts the final result. Main differences are related to the exposure related issues (i.e. exposure index, number of deaths/casualties) and to the effects on the speediness of the process (i.e. mean flow rate at the exit) also in view of the geometric features of the spaces and of the access streets (i.e. road resistor coefficient). Secondly, differences in the perception of priorities concerning the in-situ protection of the users can be noticed (i.e. temporary secure OSs, obstacle protection rate).

KPI		KPI											priority
	Decision maker: BA	2	3	4	5	6	7	8	9	10	11	12	
2	Road resistor coefficient	1,000	9,000	6,000	3,000	6,000	0,500	7,000	7,000	5,000	8,000	3,000	**0,226**
3	Pedestrian speed conservation	0,111	1,000	0,250	0,125	0,250	0,111	0,333	0,333	0,200	0,500	0,125	**0,014**
4	Obstacle friction rate	0,167	4,000	1,000	0,200	1,000	0,167	2,000	2,000	0,500	3,000	0,200	**0,042**
5	Temporary secure Oss	0,333	8,000	5,000	1,000	5,000	0,500	6,000	6,000	4,000	7,000	1,000	**0,151**
6	Exposure index	0,167	4,000	1,000	0,200	1,000	0,167	2,000	2,000	0,500	3,000	0,200	**0,042**
7	Evacuation time percentile	2,000	9,000	6,000	2,000	6,000	1,000	7,000	7,000	5,000	8,000	2,000	**0,238**
8	Crowd effects	0,143	3,000	0,500	0,167	0,500	0,143	1,000	1,000	0,333	2,000	0,167	**0,028**
9	Mean flow rate at the exit	0,143	3,000	0,500	0,167	0,500	0,143	1,000	1,000	0,333	2,000	0,167	**0,028**
10	Number of Evacuees	0,200	5,000	2,000	0,250	2,000	0,200	3,000	3,000	1,000	4,000	0,250	**0,062**
11	Number of deaths / casualties	0,125	2,000	0,333	0,143	0,333	0,125	0,500	0,500	0,250	1,000	0,143	**0,019**
12	Obstacle protection rate	0,333	8,000	5,000	1,000	5,000	0,500	6,000	6,000	4,000	7,000	1,000	**0,151**
	CR=4,4%												
	Decision maker: PM	2	3	4	5	6	7	8	9	10	11	12	
2	Road resistor coefficient	1,000	5,000	3,000	1,000	0,143	0,333	0,500	0,250	0,500	0,143	0,250	**0,035**
3	Pedestrian speed conservation	0,200	1,000	0,333	0,250	0,111	0,143	0,143	0,111	0,125	0,125	0,200	**0,012**
4	Obstacle friction rate	0,333	3,000	1,000	0,333	0,143	0,143	0,333	0,143	0,125	0,125	0,200	**0,018**
5	Temporary secure Oss	1,000	4,000	3,000	1,000	0,333	0,200	0,200	0,200	0,250	0,143	0,500	**0,032**
6	Exposure index	7,000	9,000	7,000	3,000	1,000	4,000	3,000	4,000	1,000	2,000	5,000	**0,210**

7	Evacuation time percentile	3,000	7,000	7,000	5,000	0,250	1,000	3,000	0,500	0,250	0,167	0,500	**0,073**
8	Crowd effects	2,000	7,000	3,000	5,000	0,333	0,333	1,000	0,333	0,250	0,200	1,000	**0,057**
9	Mean flow rate at the exit	4,000	9,000	7,000	5,000	0,250	2,000	3,000	1,000	2,000	0,250	2,000	**0,124**
10	Number of Evacuees	2,000	8,000	8,000	4,000	1,000	4,000	4,000	0,500	1,000	0,500	3,000	**0,138**
11	Number of deaths / casualties	7,000	8,000	8,000	7,000	0,500	6,000	5,000	4,000	2,000	1,000	5,000	**0,232**
12	Obstacle protection rate	4,000	5,000	5,000	2,000	0,200	2,000	1,000	0,500	0,333	0,200	1,000	**0,068**
	CR=9,17%												
	AGGREGATION	2	3	4	5	6	7	8	9	10	11	12	
2	Road resistor coefficient	1,000	6,708	4,243	1,732	0,926	0,408	1,871	1,323	1,581	1,069	0,866	**0,113**
3	Pedestrian speed conservation	0,149	1,000	0,289	0,177	0,167	0,126	0,218	0,192	0,158	0,250	0,158	**0,016**
4	Obstacle friction rate	0,236	3,464	1,000	0,258	0,378	0,154	0,816	0,535	0,250	0,612	0,200	**0,035**
5	Temporary secure Oss	0,577	5,657	3,873	1,000	1,291	0,316	1,095	1,095	1,000	1,000	0,707	**0,088**
6	Exposure index	1,080	6,000	2,646	0,775	1,000	0,816	2,449	2,828	0,707	2,449	1,000	**0,120**
7	Evacuation time percentile	2,449	7,937	6,481	3,162	1,225	1,000	4,583	1,871	1,118	1,155	1,000	**0,169**
8	Crowd effects	0,535	4,583	1,225	0,913	0,408	0,218	1,000	0,577	0,289	0,632	0,408	**0,051**
9	Mean flow rate at the exit	0,756	5,196	1,871	0,913	0,354	0,535	1,732	1,000	0,816	0,707	0,577	**0,075**
10	Number of Evacuees	0,632	6,325	4,000	1,000	1,414	0,894	3,464	1,225	1,000	1,414	0,866	**0,118**
11	Number of deaths / casualties	0,935	4,000	1,633	1,000	0,408	0,866	1,581	1,414	0,707	1,000	0,845	**0,085**
12	Obstacle protection rate	1,155	6,325	5,000	1,414	1,000	1,000	2,449	1,732	1,155	1,183	1,000	**0,130**
	CR=3,09%												

Figure 4. AHP matrices per terrorist risk: single decision makers and final aggregation results, including priority of the related KPIs (on the last column on the right) and CR values.

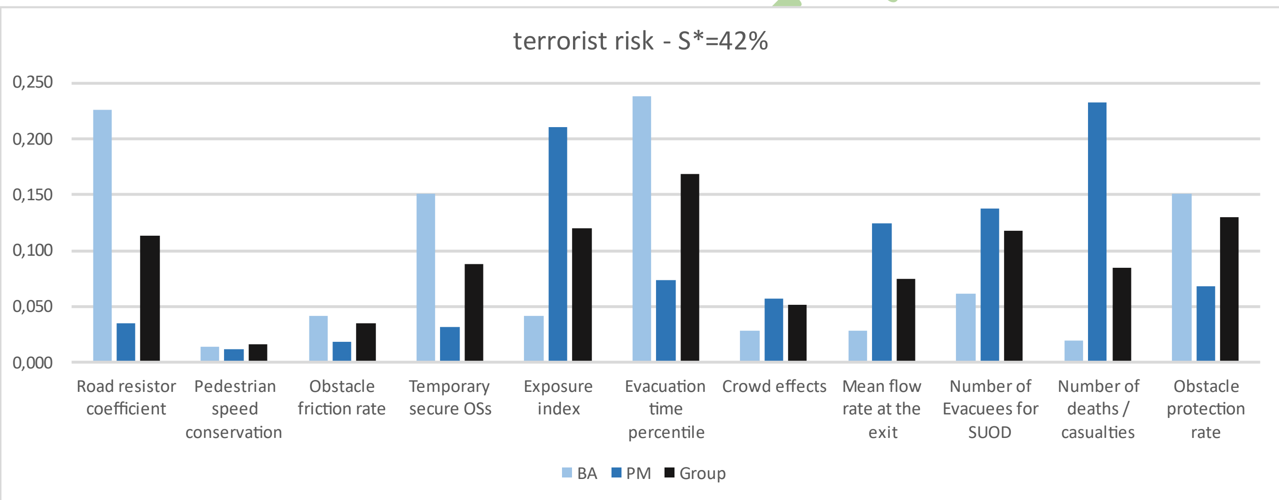

Figure 5. Priority weights for the single decision makers and for the group aggregation for terrorist risk.

After defining the priority of each KPI (last column of Figure 2 and Figure 4), the weights resulting from the AHP process are multiplied by the KPIs calculated in D 4.2.2 related to BETs analysis. This provides the final metrics for the SUODs risk assessment of each scenarios presented for the BETs under consideration.
For SUOD analysis, each BET has been analyzed according to three different geometric configurations: C1-with the presence of bollards with chains, C2-with the presence of a monument, C3-with the presence of both bollards with chains and a monument in Table 2 (see Section 3.4 in D4.2.2).
The final metric is composed of the KPIs values for each assessed BET scenario, representing the evolution of risk, from Base Scenario - minimum risk conditions, to the highest risk Scenario (SE_2 and ST_2). The whole metric distribution is then represented in the box-plot graphs of Figure 6, for each BET, thus collecting these different Table 2 scenarios and having a overview of risk in the different considered conditions.

Table 2. Summary of metrics among different risk scenarios, respectively from the left: SbE - Base Earthquake Risk Scenario (no rubble); SE1 - Earthquake Risk Scenario with two exits blocked; SE2 - Earthquake Risk Scenario with all four exits blocked; SbT - Base Terrorism Risk Scenario (false alarm); ST1 - Terrorism Risk Scenario (white-weapon attack); Terrorism Risk Scenario (vehicle attack in motion).

		SbE	SE_1	SE_2	SbT	ST_1	ST_2
BET 1A	C_1	0.171	0.362	0.658	0.121	0.409	0.430
	C_2	0.162	0.351	0.650	0.121	0.385	0.452
	C_3	0.174	0.364	0.665	0.121	0.396	0.434
BET 1B	C_1	0.083	0.323	0.582	0.112	0.347	0.347
	C_2	0.067	0.311	0.569	0.107	0.338	0.290
	C_3	0.083	0.324	0.585	0.112	0.338	0.222
BET 2A	C_1	0.186	0.359	0.705	0.161	0.435	0.418
	C_2	0.172	0.347	0.695	0.138	0.431	0.448
	C_3	0.189	0.362	0.702	0.133	0.419	0.410
BET 2B	C_1	0.090	0.318	0.622	0.116	0.349	0.231
	C_2	0.073	0.300	0.623	0.112	0.340	0.274
	C_3	0.091	0.318	0.627	0.116	0.339	0.255
BET 3	C_1	0.078	0.331	0.543	0.111	0.350	0.255
	C_2	0.068	0.320	0.520	0.106	0.337	0.253
	C_3	0.079	0.335	0.546	0.113	0.346	0.240
BET 4A	C_1	0.241	0.449	0.825	0.155	0.426	0.405
	C_2	0.226	0.439	0.826	0.145	0.403	0.416
	C_3	0.243	0.450	0.826	0.145	0.410	0.409
BET 4B	C_1	0.241	0.455	0.825	0.154	0.439	0.402
	C_2	0.226	0.455	0.826	0.146	0.408	0.420
	C_3	0.243	0.456	0.826	0.145	0.428	0.410
BET 4C	C_1	0.083	0.425	0.507	0.106	0.363	0.223
	C_2	0.071	0.417	0.511	0.101	0.319	0.276
	C_3	0.082	0.430	0.511	0.106	0.355	0.220
BET 5	C_1	0.133	0.370	0.675	0.118	0.357	0.396
	C_2	0.136	0.378	0.688	0.115	0.340	0.374

In general, seismic risk is higher than terrorism risk for all BETs and in both cases for BETs with the Special Building (1A, 2A, 4A, 4B). Special Building has a major impact in terms of the number of people attending the event, and in both cases the Exposure index (KPI 6) that directly measures the number of exposed users has one of the highest weight coefficients (0.222 for earthquake risk and 0.120 for terrorism risk). As a consequence, this weight amplifies the KPI 6 values (compare with D4.2.2, Table9.

For seismic risk, the Balance index of debris (KPI 1) and the Temporary secure OSs (KPI 5) also have a strong impact in the metrics, both of which are closely related to the amount of debris generated that progressively reduce the free plaza space, further exacerbating the risk in the smaller BETs.

For terrorism risk, the distribution of weights is more homogeneous and has acted on KPI values by going to flatten the heterogeneities that emerged in Section 3.4 of D4.2.2 among BETs.

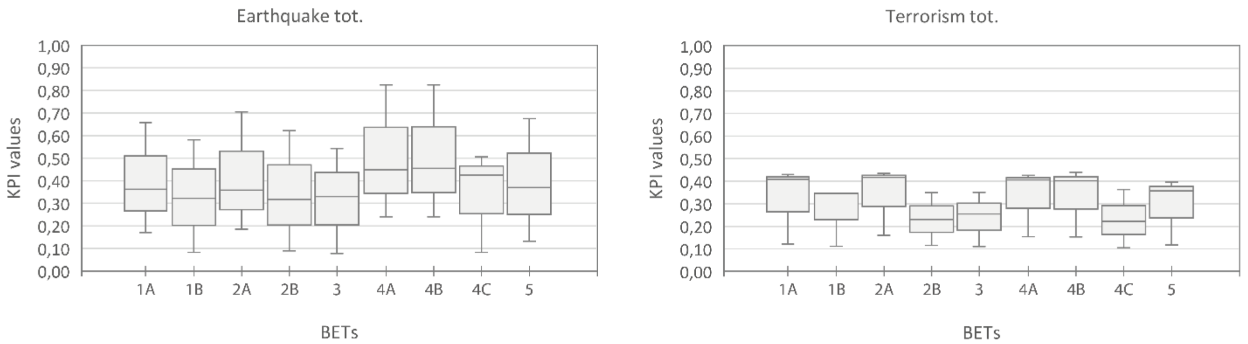

Figure 6. Summary boxplot graphs of the final metrics related to the Earthquake and Terrorism scenarios for each BETs.

3.2 SLODs metric results

Table 3 and 4 show the final metrics for increasing temperature risk, calculated from climate data for the city of Milan, Italy.
The figures show all the percentage values for each age group and the final aggregation determined by the weighted sum of these values, through the weights previously calculated as described in Section 2.3.
Figure 7 graphically compares the priorities that emerged between the two behavioral categories considered. The main aspect that emerges from the comparison of all BETs concerns the greater danger of dehydration for transient users, compared with users who remain in the BET. Particularly in the larger BETs (BET 3 and 5), where there is a large surface area exposed to the effect of heat.

Table 3. Percentage [%] of increasing temperature value given the potential 1-hour exposure of the users performing 1-hour behaviour within the BET (HW1-h), given a certain age class. Codes relating to age classes are: toddlers (TU), children (PC), young adults (YA), adults (AU), elderly (EU). The last row shows the KPI value for increasing temperature, normalized between 0 and 1

Age class	BET 1A	BET 1B	BET 2A	BET 2B	BET 3	BET 4A	BET 4B	BET 4C	BET 5
TU (0-4)	38,25	38,25	38,00	37,50	39,00	34,75	32,00	31,50	38,75
PC (5-14)	10,50	10,50	10,50	10,25	10,75	9,50	8,75	8,75	10,75
YA (15-18)	6,00	6,00	6,00	5,75	6,00	5,38	5,00	4,88	6,00
AU (20-69)	5,13	5,13	5,13	5,13	5,25	4,63	4,38	4,25	5,13
EU (70+)	5,50	5,50	5,50	5,50	5,63	5,00	4,63	4,63	5,63
Weighted sum	19,828	19,828	19,726	19,456	20,221	18,001	16,591	16,371	20,114
HW1-h	**0,198**	**0,198**	**0,197**	**0,195**	**0,202**	**0,180**	**0,166**	**0,164**	**0,201**

Table 4. Percentage [%] of increasing temperature risk value given the potential 1-hour exposure of the users performing transient behaviour within the BET (HWt), given a certain age class. Codes relating to age classes are: toddlers (TU), children (PC), young adults (YA), adults (AU), elderly (EU). The last row shows the KPI value for increasing temperature, normalized between 0 and 1.

Age class	BET 1	BET 1B	BET 2	BET 2B	BET 3	BET 4	BET 4B	BET 4C	BET 5
TU (0-4)	54,25	53,50	53,25	52,00	55,25	46,00	41,50	40,50	55,00
PC (5-14)	15,00	14,75	14,50	14,25	15,25	12,75	11,50	11,25	15,00
YA (15-18)	8,50	8,38	8,25	8,13	8,63	7,13	6,50	6,25	8,50
AU (20-69)	7,25	7,13	7,13	7,00	7,38	6,25	5,50	5,38	7,38
EU (70+)	7,88	7,75	7,63	7,63	8,00	6,63	6,00	5,75	8,00
Weighted sum	28,162	27,759	27,565	26,995	28,668	23,865	21,539	20,985	28,511
HWt	**0,282**	**0,278**	**0,276**	**0,270**	**0,287**	**0,239**	**0,215**	**0,210**	**0,285**

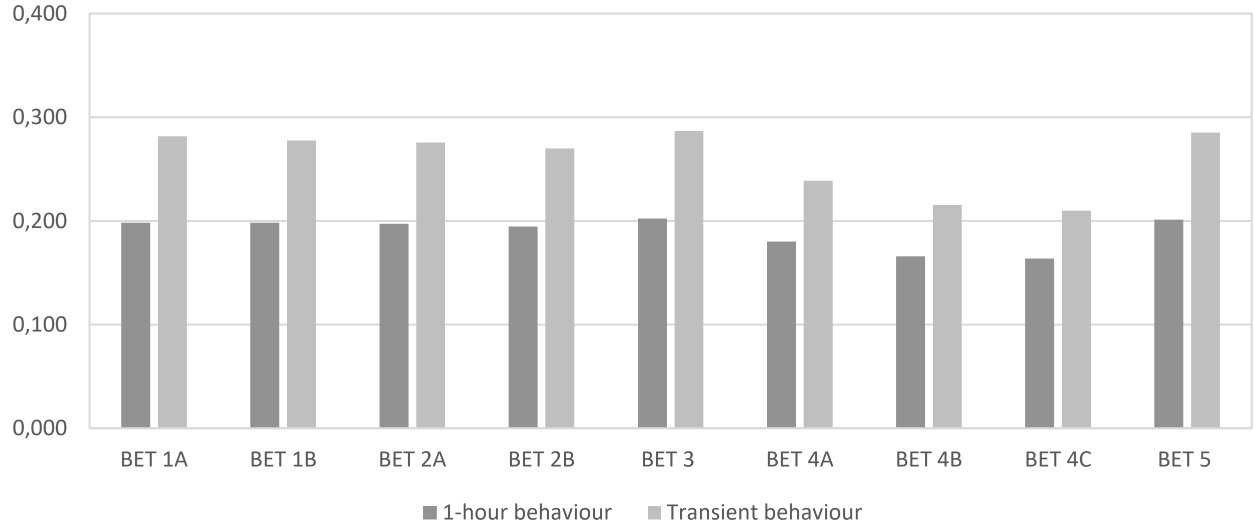

Figure 7. Comparison of the two behavioral categories for the increasing temperature KPI

Table 5 and Table 6 show the final metrics for air pollution risk, calculated from the intensity on air pollutant concentrations and distribution in Milan, Italy.
The figures show the granular pollution burden on health is estimated as the absolute increased probability of health affections [%], by considering hospital admission and mortality; and the final aggregation determined by the weighted sum of these values, considering with the same weight.
Figure 8 graphically compares the risk effects and their priorities that emerged between the two behavioral categories considered. As for increasing temperature assessment, while comparing all the BETs a greater risk level relates to transient users. Nevertheless, unlike increasing temperature, the BETs at greatest risk of air pollution are those that are the smallest ones (BET 4) and those that have a strongly asymmetrical shape (BET 1), where pollutants accumulate (see D4.2.3 and (Cadena et al. 2023)).

Table 5. Short term pollution risk [%] given the potential 1-hour exposure of the users performing 1-hour behaviour to NO2 within the BET (AP1-h) compared to a control group in an air-pollutant-free environment. The last row shows the KPI value for pollution risk, normalized between 0 and 1

Affections	BET 1A	BET 1B	BET 2A	BET 2B	BET 3	BET 4A	BET 4B	BET 4C	BET 5
Hospital admission with cardiovascular issues	0,36	0,36	0,3	0,3	0,24	0,36	0,39	0,39	0,24
Mortality	0,65	0,65	0,54	0,54	0,43	0,65	0,7	0,7	0,43
sumpond	0,505	0,505	0,42	0,42	0,335	0,505	0,545	0,545	0,335
AP1-h	0,0051	0,0051	0,0042	0,0042	0,0034	0,0051	0,0055	0,0055	0,0034

Table 6. Short term pollution risk [%] given the potential 1-hour exposure of the users performing transient behaviour to NO2 within the BET (APt) compared to a control group in an air-pollutant-free environment. The last row shows the KPI value for pollution risk, normalized between 0 and 1.

Affections	BET 1A	BET 1B	BET 2A	BET 2B	BET 3	BET 4A	BET 4B	BET 4C	BET 5
Hospital admission with cardiovascular issues	0,48	0,48	0,42	0,42	0,33	0,48	0,51	0,51	0,33
Mortality	0,86	0,86	0,75	0,75	0,59	0,86	0,92	0,92	0,59
sumpond	0,67	0,67	0,585	0,585	0,46	0,67	0,715	0,715	0,46
APt	0,0067	0,0067	0,0059	0,0059	0,0046	0,0067	0,0072	0,0072	0,0046

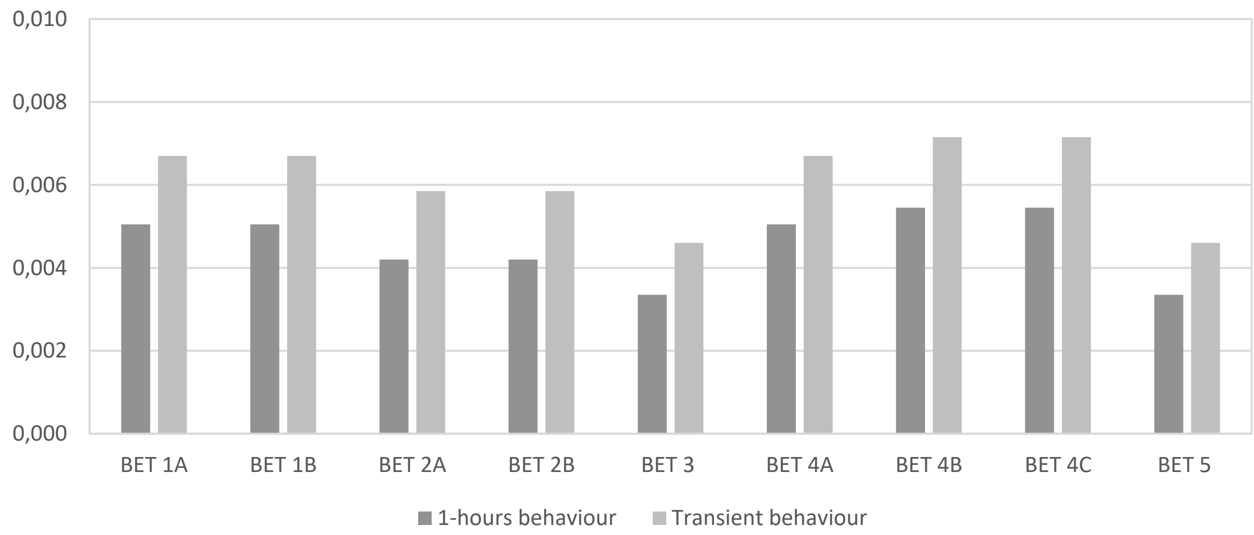

Figure 8. Comparison of the two behavioral categories for the air pollution KPI

Aggregating the SLODs risks according to Equation 3 (Section 2.3) showed a general alignment of results for all BETs. However, a higher risk can be observed for the larger BETs, in accordance with the risk from increasing temperature having a greater impact on the final metric, with an order of magnitude of the values much larger than for air pollution. This implies that increasing temperature determines the overall risk trend while air pollution acts as a corrective on the final result. Figure 9 graphically shows the final metric for SLODs risk.

Figure 9. Final SLODs metric

3.3 Final risk vectors

A preliminary analysis on the variation in risk between geometric (layout) configurations has been performed. In fact, as pointed out in Section 3.1, for SUOD investigations, three different geometric configurations have been considered. However, for the comparison with SLOD risks, only configuration C3 (bollards with chains and monument) has been considered because it is the most complex and because there are no particular differences with the other configurations. Only for BET 5 configuration C2 (only monument) has been considered since the C3 configuration is not provided for this BET. Nevertheless, the variation of risk depending on the layout is never greater than 5%, thus assuming that similar trends are noticed in the different simulated conditions.

Table 7. Summary of possible single and multi-risk combinations for each BET defined in D3.2.1

Risk	BET 1A	BET 1B	BET 2A	BET 2B	BET 3	BET 4A	BET 4B	BET 4C	BET 5
E	-	-	+	+	-	+	+	+	-
T	+	-	+	-	-	+	+	-	-
H	+	+	+	+	+	+	+	+	-
P	+	+	+	+	+	-	-	-	-
Characterising risks	T+P+H	P+H	S+T+P+H	S+P+H	P+H	S+T+P	S+T+P	S+P	-

E = Earthquake risk; T = Terroristic risk; H = Heatwaves risk; P = Air Pollution risk;
+/- = more or less prone to specific risk.

Observing the risk matrix in Figure 10, it appears that the most at risk SUOD BETs (SE and ST) are BET 4A/4B, following by BET 2A as expected from the preliminary observations made in D3.2.1 (D'Amico et al. 2021) and summarized in Table 7. For earthquake it is certainly the small size of BET 4 that determines the high risk, as debris risks occupying all the space. For terrorism the situation becomes more difficult, it is the morphological complexity of the BET, rather than the size that increases the risk. While for SLODs there is a substantial difference between the two types of hazards. For Heatwave, the worst BETs are the largest ones, i.e. 3 and 5, where the shade determined by the buildings is insufficient to cover the entire square, and for 5, green areas with trees are not counted since people are not expected to be present in them. For Air Pollution, meanwhile, the smallest BETs are the worst, since pollutant particles are trapped.

Risk	BET 1A	BET 1B	BET 2A	BET 2B	BET 3	BET 4A	BET 4B	BET 4C	BET 5
SE	0,449	0,389	0,469	0,409	0,372	0,561	0,562	0,388	0,460
ST	0,346	0,242	0,347	0,254	0,252	0,344	0,353	0,249	0,299
SH	0,240	0,238	0,236	0,232	0,244	0,209	0,191	0,187	0,243
SP	0,007	0,007	0,006	0,006	0,005	0,007	0,007	0,007	0,005

Figure 10. Matrix of single-risk vectors for each BET. The gradient represents the risk level of each BET compared with the median for each risk. White: low risk - Red (based on intensity): from medium risk to high risk.

The Figure 11 represents the final multi-risk vectors, resulting from combining the 4 risks according to Section 2.4. This combination represents the worst possible scenario, one in which all risks are overlapped. BETs 4A and 4B are confirmed as the riskiest, with a forcing from the D3.2.1 forecast, which excluded the risk from heat waves in the possible risk combination for this BET. This is followed by BET 2A, which instead confirms the D3.2.1 forecasts since it is the only one for which the combination of all 4 risks has been assumed.

	BET 1A	BET 1B	BET 2A	BET 2B	BET 3	BET 4A	BET 4B	BET 4C	BET 5
S_{TOT}	0,308	0,258	0,315	0,267	0,256	0,345	0,345	0,249	0,300

Figure 11. Matrix of multi-risk vectors for risk. The gradient represents the overall risk, allowing comparison between the analyzed BETs. From lowest risk (dark green) to highest risk (red)

4. Conclusions and remarks

The development of risk and resilience matrices could be supported by multi criteria decision making strategies, which can weigh the impact of different Key Performance indicators on the final result, according to the expertise of the decision makers. In this sense, the Analytical Hierarchy Process (AHP) is one of the most powerful approaches, since it is supervised in terms of consistency ratio of prioritization, and it could be also easily implemented in decision group making. This approach has been used for both SUOD and SLOD risk in different ways.

The proposal of KPIs as shown in D4.2.2 and D4.2.3, is used to create the final risk metrics. For SUODs, this work collects the AHP related to the partners of the research project, by providing risk matrices (one for each partner) and then their aggregation. Results also point out the average consensus between the different involved decision makers, by suggesting which differences are correlated to the prioritization weights. Since this work focuses on risk in a separated manner (i.e. two matrices are propose for seismic and terrorist risks), future works could apply the same approach by combining the same indexes together, or even the final results of the assessment. For SLODs, a unique AHP-based metric is defined and combines heatwaves and air pollution effects on the users. The metrics for SLODs and SUODs seem to be able to point out the main criticalities of each BET, thus ensuring their applicability also to retrofit strategies assessment, which will be discussed in D5.2.1. The proposed method, in fact, is easy to implement thanks to the fact that each final judgment through the AHP priorities associated to each KPIs will vary from 0 (minimum risk, so maximum resilience) to 1 (as maximum risk, so minimum resilience). This ensures quick comparison between different scenarios and highlights the impact of each KPI affecting risk. At the same time, the method considers the basic elements affecting risks in the built environment and its application could be extended also to case study scenarios, and not only on the BETs.

Finally, the synthetic representation using multi-risk vectors ensures a quick and effective comparison to identify the most at-risk BETs. As with metrics, this representation can also be easily applied to mitigation strategies, as then demonstrated in WP5 and WP6 activities, respectively on the BET and on the analyzed case studies.

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BE S2ECURE project D 3.2.1 | Basic BETs configuration and typical combinations