# 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**

Risk and resilience assessment can take advantages of the definition of recurring conditions of the Built Environment, through the identification of Built Environment Typologies (BETs), on which simulation tools can be applied to identify the main issues in emergency conditions. On these bases, the current deliverable traces the results of the application of agent-based simulation model developed by D4.1.1 on the BETs identified by D3.2.1, depending on the exposure conditions in D3.2.3. Current scenario conditions are assumed, by thus representing the BET as it is defined in the typological representation. Simulations are organized in two main groups: 1) Slow Onset Disasters (SLODs - heatwaves and pollution implying the permanence of users in the outdoor BET) are assessed by themselves through simplified models relying on the relation between users and the BET conditions; 2) SLOD are then considered as input scenarios for Sudden Onset Disasters (SUODs) implying evacuation in (earthquake) or from (terrorist act) the BET. The basic key metrics (e.g. evacuation times for SUODs; exposure time for SLODs) defined in D4.1.1 are then used to trace preliminary results from the BETs application, in view of a more extensive assessment through next actions concerning behavioural-based Key Performance Indicators (KPIs) and metrics development (as shown in D4.2.2 and D4.2.4). Results for the different BETs are also compared to understand them and point out the main characterizing issues for users' safety in the BETs.

**Keywords**

Disaster simulation; human behaviour; risk assessment; key performance indicators

## Approvals

| Role | Name | Partner |
|---|---|---|
| Coordinator | Enrico Quagliarini | UNIVPM |
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## Revision versions

| Revision | Date | Short summary of modifications | Name | Partner |
|---|---|---|---|---|
| 0.1 | 10.05.2022 | Updating simulation results by increasing the sample dimensions | Gabriele Bernardini | UNIVPM |
| 0.2 | 12.10.2022 | Proofread, figure editing and adding of boxplot distribution for earthquake and terrorist risk assessment | Gabriele Bernardini | UNIVPM |
| 0.3 | 20.06.2023 | Improvement of figure editing and update of references according to the 2023 work publications (i.e. Quagliarini et al. 2023a and 2023b; Cadena et al. 2023) | Gessica Sparvoli | UNIVPM |

## Summary

## 1. Introduction

The combination of Slow Onset Disasters (SLODs) and Sudden Onset Disasters (SUODs) can lead to critical conditions in the Built Environment (Curt 2021), not only from a temporal standpoint but also because the SLOD-affected variation of users' habits can impact the initial conditions for SUOD response (e.g. varying the number or the position of exposed users in the POSs).

Previous activities of the BE S2ECURe project succeed in identifying how squares are affected by such kinds of risks, adopting a multi-risk perspective, thus outlining the main features of such BEs (i.e. see D3.1.1), identifying different Built Environment Typologies (BETs) based on the statistical analysis of data from a wide sample of squares (i.e. see D3.2.1 and (D'Amico et al. 2021)), and also describing the main users' factors trends over time thanking to the same real-world case study analyses approach (i.e. see D3.2.3 and (Quagliarini et al. 2023b)). In this sense, although the retrieved BETs and users' factors trends are representative of Italian historical cities, where case studies are collected, the method can be applied to any other national/international context.

Anyway, the "concurrence" of such disasters highly underlines how a dynamic risk assessment approach is needed (Curt 2021), by including a behavioural perspective to evaluate the impact of emergency conditions on the BE and its users (Bernardini et al. 2016a).This Behavioural-Design (BD) approach for risk assessment and proposal of risk-mitigation strategies takes advantage of experimental-based simulation models to reproduce emergency conditions and include human behaviours in the overall analysis, moving towards sustainable planning of solutions in the historical urban built environment. While most of the works focused on full or partial urban scale simulation, some efforts on single SLOD and SUOD simulation-based analysis in a single BE or BET have been carried out (Wagner and Agrawal 2014; Yıldız and Çağdaş 2020; Bernardini and Ferreira 2022). To the authors' knowledge, coupled risks (Curt 2021) have not been investigated yet. To solve this issues, D4.1.1 activities defined a simulation model for replicating and analysing SLOD-to-SUODs conditions starting from the BD-based approach. The model can describe initial SLOD conditions affecting the users' distribution over the BE/BET outdoor spaces, essentially depending on the heatwave severity through the UTCI values. Then, SUODs can be separately simulated to reproduce the evacuation process, i.e. in earthquake (people enter the square to look for shelter) and terrorist act (people leave the square where the attack happens) emergency conditions. This multi-agent model relies on probabilistic and microscopic approaches (Ronchi et al. 2014; Kuligowski 2016; Lumbroso and Davison 2018), and uses a granular methodology to simulate users' motion over time thanking to a cellular automata approach (Li et al. 2019) developed within the NetLogo platform (Wilensky 1999). The simulator features and use are reported in D4.1.1 and in the software manual3.

The capabilities of the BD approach could be applied to the modelling of the real world case studs, but their results are quite hard-to-be generalized. BEs decision-makers, such as public local authorities, and their technicians should be hence supported by quick methodologies, such as those relying on typological risk-mitigation solutions that could be "tailored" to each case study specificities (D'Amico et al. 2021). Therefore, reasoning on the BE Typologies (BET) could be more effective than testing single scenarios since their recurring conditions can be assessed in a more feasible way. Similarly, using typological conditions concerning users' exposure and vulnerability can be useful too, since simulations can assessed the impact of statistically recurring scenarios of the BETs.

This work hence applies D4.1.1 simulation model to the BETs defined in the BE S2ECURe project, that are shown in Figure 1 according to D3.2.1 activities on the classification of real world case studies in the Italian context (see also (D'Amico et al. 2021)). Simulation in the SLOD-to-SUOD perspective considers heatwave-to-earthquake and heatwave-to-terrorist act emergency conditions. Typological users' exposure and vulnerability conditions are then considered according to D3.2.3 results (see also (Quagliarini et al. 2023b)).

Outputs from the simulation are defined to compare the different conditions of the BETs, which also include different outdoor spaces layout and specificities of each simulated SUOD. These outputs are also defined to be consistent with the Key Performance Indicators requests of the other WP4 – T4.2 actions (i.e. see D4.2.2 - Section 3).

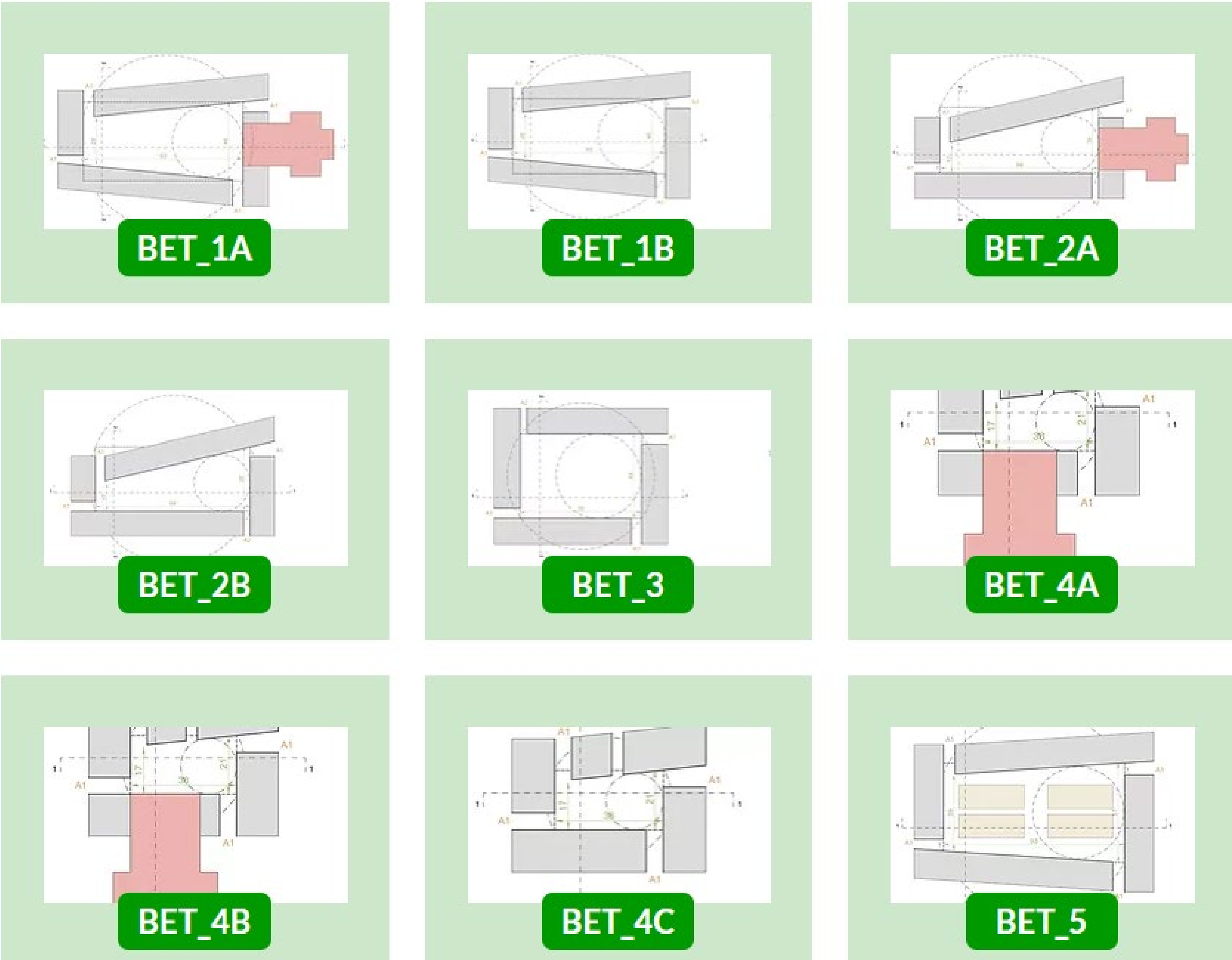


*Figure 1. BETs plan view and schematization according to D3.2.1 classification. Image from [https://www.bes2ecure.net/wp3](https://www.bes2ecure.net/wp3)*

## 2. Methodology and phases

The work is organized in three main phases. The first phase concerns the definition of common input conditions for the simulation of each scenario for BET simulations in the SLOD-to-SUOD logics (see Section 2.1). The second phase concerns the criteria for simulation runs, focusing on repetitions and outputs assessment (see Section 2.2). The third part concerns the comparisons between the simulation outputs to trace general conditions of each BET and each BET configuration according to the first work phase inputs (see Section 2.3).

### 2.1 Input conditions definition

The input conditions essentially refer to the following main aspects: 1) the built environment, including the outdoor spaces layout (section 2.1.1); 2) the SLOD conditions, i.e. focusing on heatwaves as it affects the initial users' positions at the simulation starting, and the SUOD conditions, that are terrorist acts implying evacuation from the BET and earthquake implying the "invacuation" in the BET and the collection of users by the neighboring linked streets (section 2.1.2); 3) the users, by pointing out the quantity and typologies of simulated agents (section 2.1.3); and 4) the definition of constant parameters, which can be correlated to the specific simulated disaster conditions (section 2.1.4).

### 2.1.1 Built environment inputs

The built environment input definition is performed according to the BETs definition of D3.2.1 (D'Amico et al. 2021), which provides the general geometrical and morphological factors of the BET, and points out the presence of a special building in the BET (implying possibility to host local higher users' densities).

In each of these configurations, the presence of dehors is also considered. The dehors dimension is provided according to D3.2.3 results on the classification of the outdoor areas depending on their use by people (see D3.2.3, Section 3), expressed in terms of percentage, as the ratio between dehors area and the BET outdoor area. In general terms, the analysis of real-world case studies in D3.2.3 pointed out a median percentage of dehors area equal to about the 4% of the whole public open space area (see also (Quagliarini et al. 2023b)). These dehors are then considered as fenced areas with two exits, hosting prevalent outdoor users. The dimensions of the dehors are evaluated according to standard modular solutions commonly available on the market, i.e. rectangular or squared modules with sides length ranging from 3 to 5m. Finally, the dehors are placed on the west side of the BET, because: 1) statistics on the case studies of D3.2.3[1] show that they are mainly placed on a single square side; 2) this can minimize the impact of SLOD conditions, i.e. heatwaves, maximizing the probability that people can gather in these areas in the time span from 11 to 16 (compare section 2.1.2).

BET types A and BET 4B are also characterized by a special building hosting higher densities of people according to the BETs definition of D3.2.1 (D'Amico et al. 2021). The area of this special building is always equal to about 1200mq, that is the mean value of real-world special buildings in the D3.2.3 case studies, see Section 3 (compare also (Quagliarini et al. 2023b)).

On these bases, three different outdoor layout variations have been considered to take into account the presence of specific obstacles in the public open space, that are: a) poles along the carriageway crossing the BET (see **Errore. L'origine riferimento non è stata trovata.**), to consider common solutions to divide the pedestrian area and the driveway[2]; b) a central monument, whose area is equal to the 2% of the outdoor area, according to D3.2.3-Section 3 statistics on unwalkable areas, and which can represent a central fountain, sculpture or fenced greenery (reducing the available area in case of an earthquake and being an obstacle in case of terrorist act evacuation – see **Errore. L'origine riferimento non è stata trovata.**); c) both of them (see **Errore. L'origine riferimento non è stata trovata.**)[2]. These layout configurations allow to distinguish different conditions to users' distribution and flows in both SLOD and SUODs.



[1] see raw data at: https://univpm.sharepoint.com/:x:/r/sites/be.s2ecure/Documenti%20condivisi/WP3/T3.2/DELIVERABLE/Piazze%20D323/Analisi%20Dehor_211011_GB+MR.xlsx?d=w13c96a8ddb7440239b0167cdb411ea5e&csf=1&web=1&e=Lz9gTm

[2] for BET5, poles are not included since the central area is functionally divided by the driveway according to its geometry. Thus, the poles and monuments configuration is also ignored.

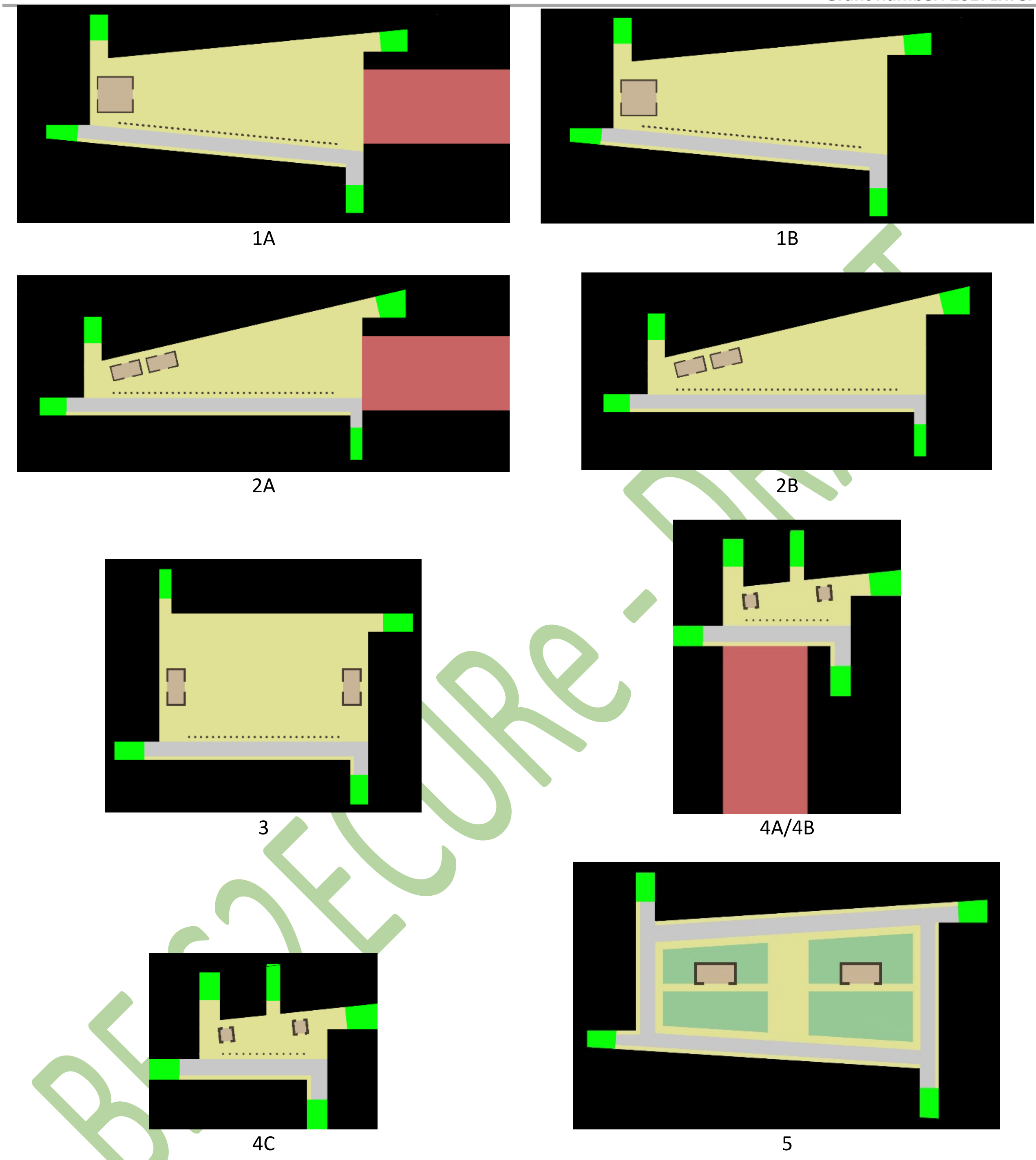


*Figure 2. Summary of the BET conditions for the layout with poles along the carriageway crossing the BET. Panels are shown in relative scale.*

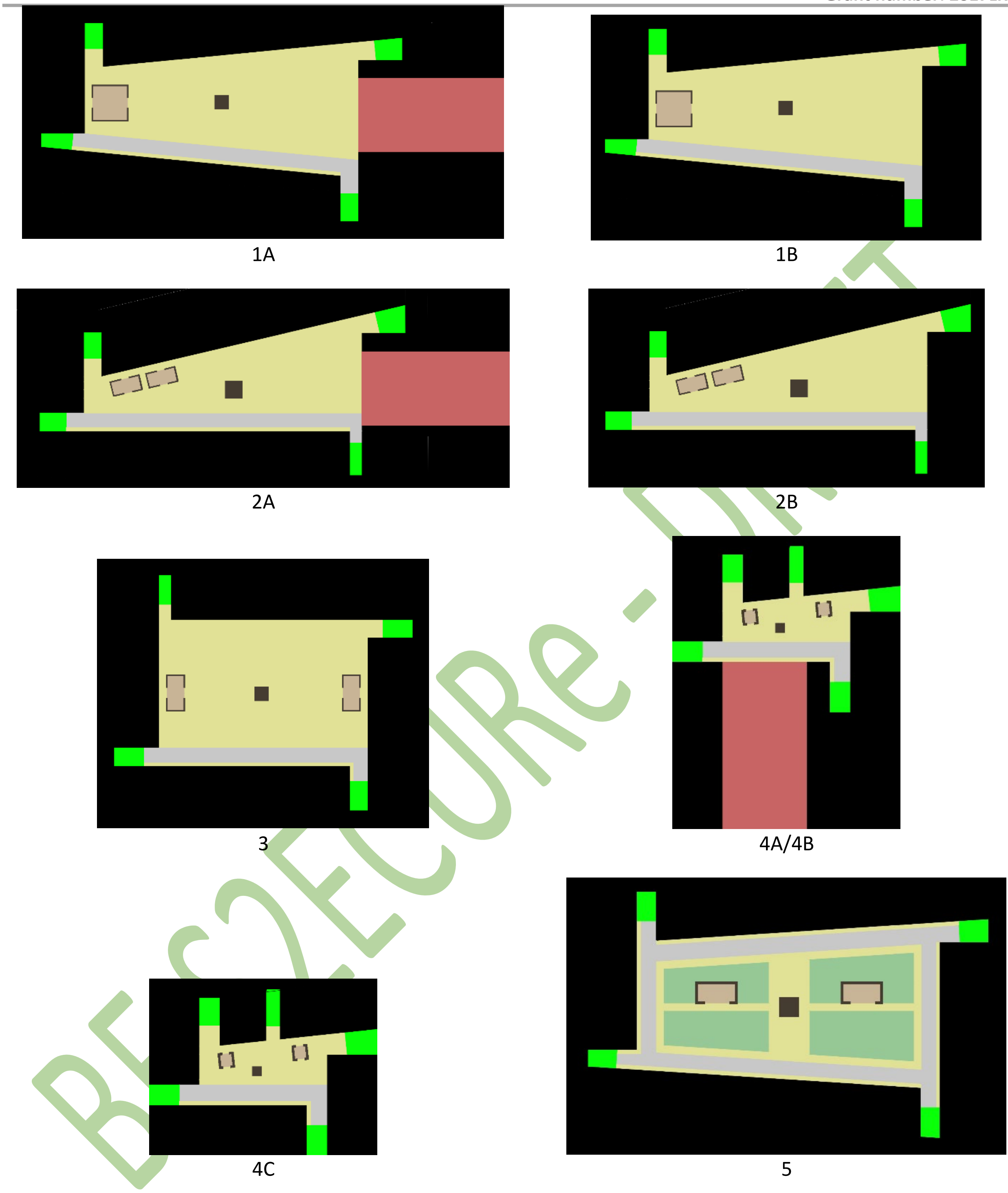


*Figure 3. Summary of the BET conditions for the layout with a central monument. Panels are shown in relative scale.*

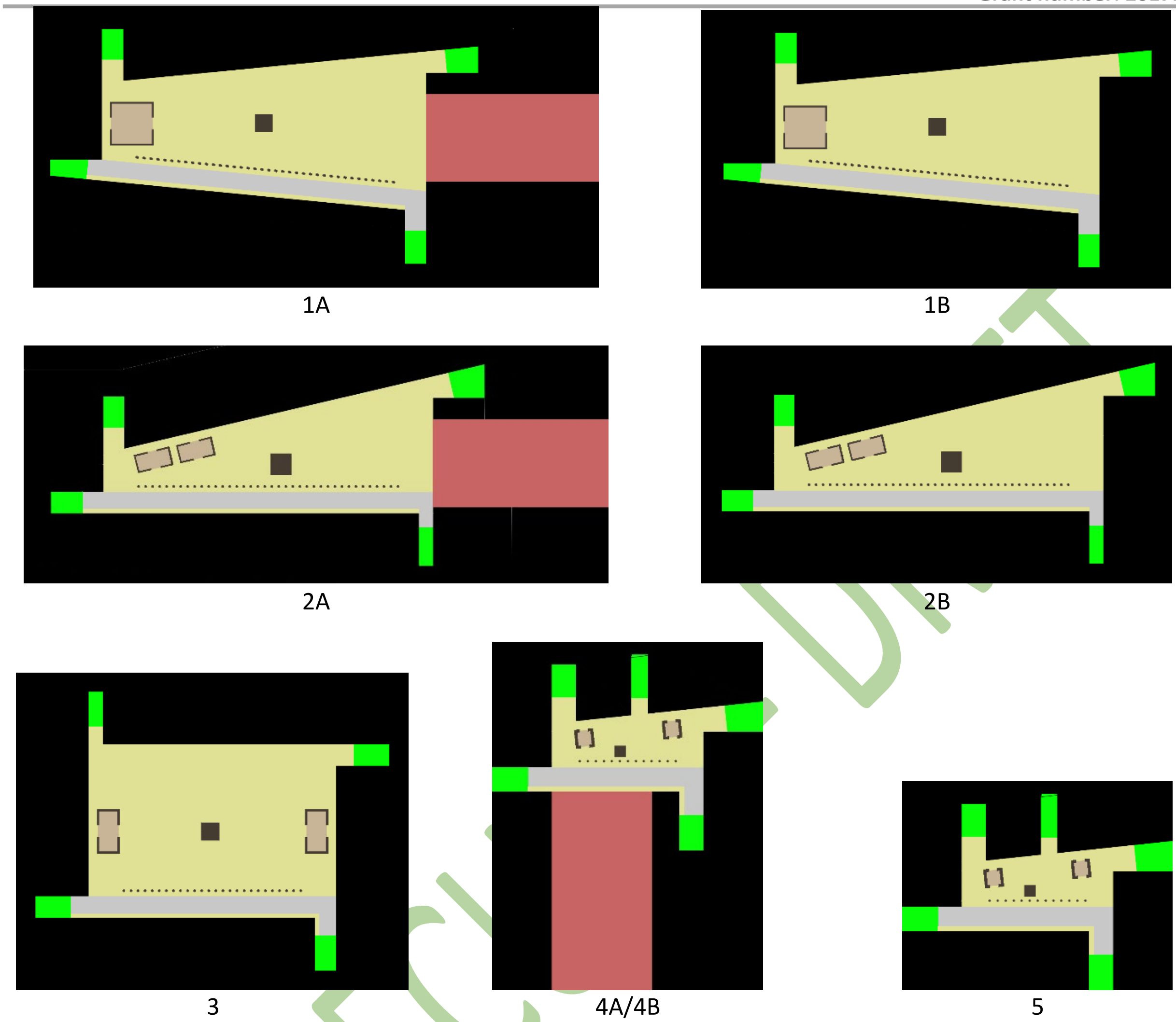


*Figure 4. Summary of the BET conditions for the layout with poles along the carriageway crossing the BET and the central monument. Panels are shown in relative scale.*

### 2.1.2 SLOD and SUOD inputs

SLODs conditions are referred to heatwaves in the outdoor spaces of the BET, according to simulations via ENVIMet, as shown in general rules of D4.1.1, Section 4. UTCI values in the 5m x 5m grids shown in D4.2.3, Section 3 are used to populate the scenario according to the thermal acceptability thresholds (Cheung and Jim 2019). In particular, simulations consider the environmental conditions referring to the city of Milan during the time span 11AM-4PM, as the most critical time span in summer day as well as the most representative of a typical scenario in both Italian and European context too (see indeed D4.2.3, Section 3). Figure 5 resumes an example of these UTCI maps in a typological context.

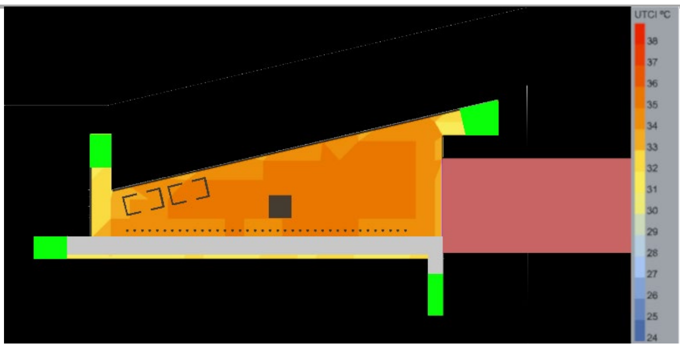

*Figure 5. Example of BET UTCI [°C] scheme (hours: 11AM to 4 PM): BET 2A (colour map on the right).*

Concerning SUODs, three earthquake scenarios and four terrorist acts scenarios are considered as input ones, as shown in the summary of Table 1. They are separately simulated according to the general criteria of D4.1.1, Section 3 and Section 4.

*Table 1. Summary of SUODs scenarios.* refers to baseline simulations conditions for the specific SUODs*

| **Earthquake – return time: 475 years** | **Terrorist act** |
|---|---|
| No damage* | "False alarm"* |
| Intermediate damage (vulnerability differences between the built fronts) | Bombing attack (static conditions, the bomb explodes and then the evacuation starts) |
| Collapse conditions | Weapon attack (dynamic conditions: the attackers tries to catch the users) |
| | Vehicle running into the crowd (dynamic conditions: the vehicle moves along a straight line) |

The earthquake scenarios (static conditions: damages are considered generated all at the starting of the simulation) regard the "invacuation" in the square, thus collecting people from the outdoor BET open space, the surrounding buildings and the linked streets, in case of: a) no damage in the square, as baseline reference for the process (Figure 6-scenario 1); b) intermediate damage, due to differential vulnerability of structures causing damages to the western exits of the square, which are the ones with higher probability of occupancy by outdoor users in view of the lower UTCI values (Figure 6-scenario2); c) collapse conditions, in which all the buildings have the same vulnerability and so the same damage level (Figure 6-scenario 3). All the scenarios refers to a return time of 475 years, leading to critical damages outdoors in probable conditions (compare (Bernabei et al. 2021) and D2.2.1, Section 3). Complete data on the BETs input are reported in https://univpm.sharepoint.com/:f:/r/sites/be.s2ecure/Documenti%20condivisi/WP4/T4.1/UNIPG/V3_ALTEZZE%20OMOGENEE%20-%20VULN.%20DIVERSA?csf=1&web=1&e=2lhi5U.

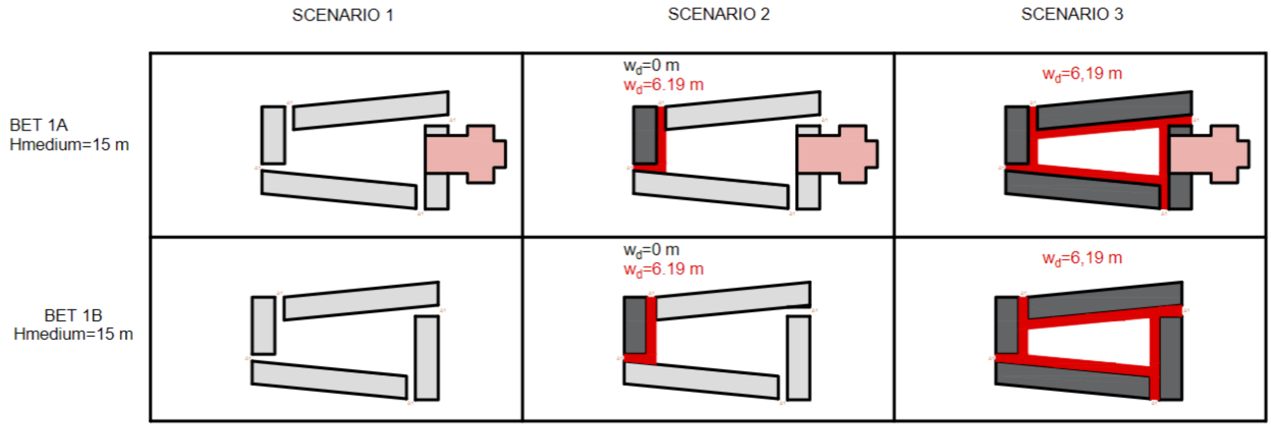


*Figure 6. Example of BET damage conditions for earthquakes, in the case of BET 1: scenario 1, on the left, as "no damage" conditions; scenario 2, on the middle, as intermediate conditions due to differences in buildings vulnerabilities; scenario 3, on the right, as collapse conditions due to homogeneous buildings vulnerabilities.*

Figure 7 shows the scheme of the attack typologies implying direct effects on the users by overlapping a graphical representation of the risk in the BE open space due to the SUOD $R_{c,t}$ [-] values for the cells 8see D4.1, Section 3 and Section 4). In each typology, it is considered that the attack is performed where most of the users are gathering, thus in front of the special building (i.e. the church) for BET types A and BET 4B, or in the dehors area for BET types B and BET 4C. The bombing attack assumes a static number of casualties inside the attack area (red circle in Figure 7-a having about 10m of diameter to consider a sort of simple homemade bomb), while "vehicle running into the crowd" and "attack with a weapon" are dynamically simulated during the evacuation time. The vehicle moves from the carriageway to the opposite side of the outdoor space towards the crowd (arrow in Figure 7-b). 2 attackers with weapons start moving in the crowd (within the red circle in Figure 7-a), then chase them up to the end of the evacuation process, by killing users inside a 1m radius. In these attack typologies, it is conservatively assumed TSAP=50% (compare D4.1.1, Section 4 and the software manual[3]. The "false alarm" does not include casualties and all the outdoor space cells have $R_{c,t}$=1. Figure 8 resumes the specific conditions for the weapon and bomb attack point and the related risk maps, from white (maximum risk) to dark brown (minimum risk for maximum distance).

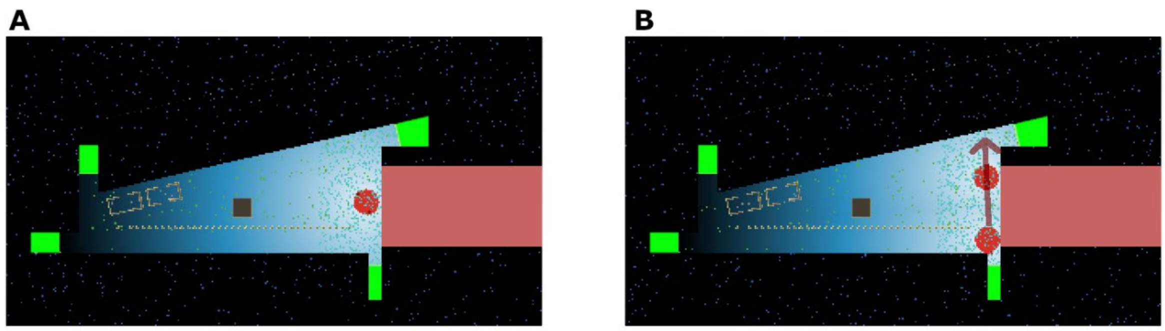


*Figure 7. Example of terrorist attack conditions for a BET (BET 2A for layout with poles and monument): (a) bombing and weapon attackers, starting in the red circle; (b) vehicle running into the crowd placed in front of the church, moving along the arrow direction linking red circles. Users' are blue points, while risk map at time=0s ranges from white (Rc,t=0, thus maximum risk) to dark blue (Rc,t ≈1, thus minimum risk).*

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[3] Sharepoint BE S2ECURe

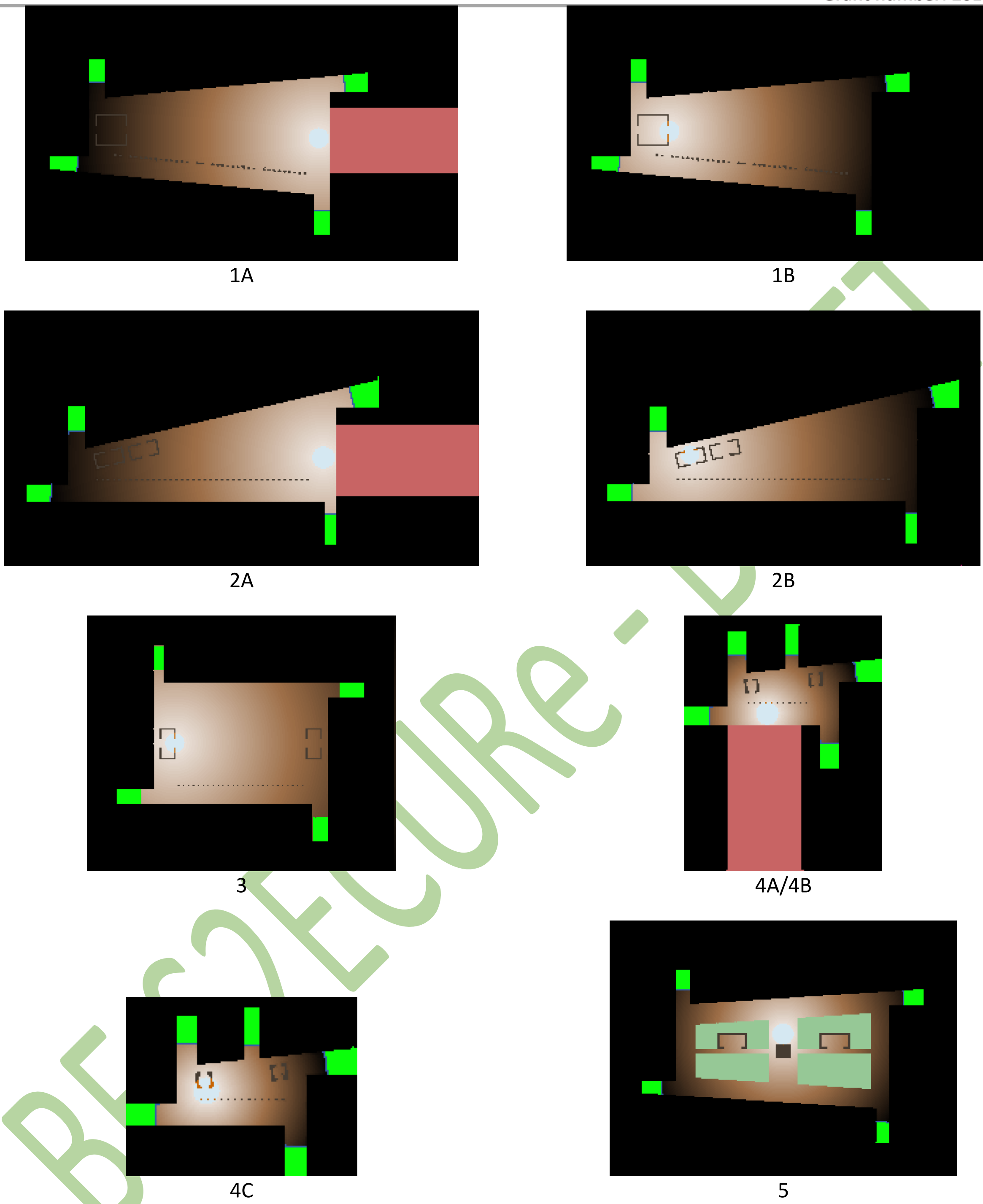



*Figure 8. Summary of the bomb and weapon attack for the BET (examples in respect to a reference layout).*



### 2.1.3 Users' inputs

Users' inputs mainly concerns the quantity of people to be simulated and their features, according to D3.2.3, Section 3 results (see also (Quagliarini et al. 2023b)). Table 2 summarizes users' input data conditions distinguishing between working days (W) and holidays (H) patterns, in terms of maximum (max), median (med) and minimum (min) conditions of the parameters depending on experimental analysis on the D3.2.3 case study. In particular, simulations are mainly focused on working days (W) conditions and median values, since they are the most recurring one all over the year. Anyway, to increase the number of exposed people, the special buildings is considered as open to the public, implying an additional load of 0.4pp/m$^2$ (that means about 480 people in each BET since the building area is always about 1200m$^2$, see Section 2.1.1). These users are generated in front of the special buildings, waiting for entering them, so as to increase critical outdoor density conditions.

In both earthquake and terrorist act simulations, in case pedestrian density is >4pp/m$^2$, or the evacuation speed reduces suddenly (more than 0.3g of acceleration between two consecutive time ticks), or the user is moving in a counterflow, the user can stop his/her motion because of physical contacts and falls at the ground, depending on a probability threshold (5%) comparison by a random number (Lakoba et al. 2005; van der Wal et al. 2017). He/she will wait up to about 30s according to a random uniform distribution (van der Wal et al. 2017).

Finally, users' speed in earthquake are derived according to the speed-density relations of (Bernardini et al. 2016b), while the ones in terrorist acts are derived according to D1.3.3, Section 3 data.

A complete overview of these inputs is also discussed in Section 5 of the simulation model manual[3].

*Table 2. Outline of the typological description of the BETs according to the median values of KPIs of D3.2.3-Section 3, considering working days (W) and holidays (H) patterns, in terms of maximum (max), median (med) and minimum (min) conditions. Parameters marked by * are used in this work as the recurrent conditions for non-normal trends in input values.*

| KPI | Max (W : H) | Med (W : H) | Min (W : H) |
|---|---|---|---|
| **UOOd [pp/m2]** | 0.55 : 0.36 | 0.22* : 0.20 | 0.06 : 0.06 |
| **OOp [%]** | 48 : 49 | 15* : 23 | 0 : 0 |
| **POp [%]** | 6 : 4 | 1* : 1 | 0 : 0 |
| **NRp [%]** | 82 : 67 | 48* : 33 | 0 : 0 |
| **Common values in both W and H** | | | |
| **SBd [pp/m2]** | 0.4* (most common depending on building uses) or 0.7 (conservative, i.e. could be chosen for H) | | |
| **Areas dimension for the BET simulation** | *Special buildings:* 1200mq<br>*Square area (outdoor):* depending on the BET configuration<br>*Vehicular area:* 30%<br>*Pedestrian area:* 65%<br>*Dehors:* 2 to 5%<br>*Permanent obstacles:* 1 to 2% | | |
| **FSUp [%]** | *For terrorist act:* 0*<br>*For earthquake:* 31 (Q1); 45* (median); 64 (Q3) | | |
| **TUp [%]** | 4* | | |
| **PCp [%]** | 9* | | |
| **YAp [%]** | 5* | | |
| **AUp [%]** | 64* | | |
| **Fp [%]** | 52* | | |

### 2.1.4 Other constant parameters

Besides users' input, the following parameters were considered as constant in the simulations depending on the tested SUOD.

In earthquake evacuation, it is considered that ***SAP***=88% (Kang et al. 2017) and that non collapsed buildings area are still minimized to maximize the number of simulated users according to a conservative approach without any additional data on building internal damage (thus, ***noncollapsed***=100%). A preliminary evaluation of the general conditions in earthquake motion far from buildings and evacuation stop suggested us to select ***seismicdistfin***=1 and ***seismicrandompatch***=500, so as to make people looking for the center of the square allowing first evacuees to stop at a safety distance from the buildings and the debris without blocking the rest of the evacuees. Then, the ***Alfa, beta, gamma, delta*** values are assumed as 0, 0.75, 0, 0.25 according to the same preliminary evaluation, implying that: 1) people are mainly aware of debirs and buildings damage (fear of buildings), are available to move close in the evacuation while avoiding physical contacts; and 2) the evacuation process curves converging over the evacuation time.

In terrorist act simulation, ***TSAP***=50% except for "false alarm" (TSAP=100%, implying no casualties due to the attack). In this case, the evacuation motion is essentially lead by the reaching of a BET exit as evacuation target, thus considering only ***beta***=1.

A complete overview of these inputs is also discussed in Section 5 of the simulation model manual[3].

## 2.2 Criteria for simulation runs and outputs of the simulations

In each BET simulation, according to general guidelines on evacuation simulation (Ronchi et al. 2013), at least 10 runs of each setup scenario are performed to keep in mind modelling uncertainties, and then verifying that the percentage standard deviation at the evacuation time of the 95% of evacuees should be ≤5%, as the main simulation goodness indicator. In case this threshold is not reached, additional simulations are performed until these simulation outputs converge under 5%. This mean percentage standard deviation is then reported to show the behavioral uncertainties dimensions for each scenario.

A complete overview of the software outputs is also discussed in Section 6 of the simulation model manual[3]. In the following, these output data are considered as essential to describe each BET condition, and then to compare different scenarios according to previous works on other SUODs analysis (e.g. fires, earthquakes) (Ronchi et al. 2013; Wagner and Agrawal 2014; Bernardini and Ferreira 2022):

- Evacuation curves under median crowding condition, in terms of the number of users reaching a safe area in the BET over the time, to depict a general view of the users-BET-attack interactions;
- Evacuation time T95 [s] and related flows F95 [pp/s] at the safe areas, by considering the 95% of the users to avoid considering effects due to "outlier" model uncertainties, e.g. initial users' positions, speed calculation, cells selection and motion loops. The higher T95, the higher the risk since users do not quickly abandon their initial hazardous position. Higher F95, higher the evacuation "speediness" given the hosted users' number;
- Median number of casualties directly due to the attack C [pp], which increases with the risk;
- Median numbers of users who complete the evacuation during the simulation time AP [pp], as safety indicator, and of users who did not complete it NE [pp], but who are not included in the casualties, as a risk indicator. These data could be also reported in percentage terms to disregard the users' quantity at the starting of the process;

- Relative number of physical contacts among users and falls PCF [events/s], to investigate effects of dense crowd motion and obstacles interactions. Dividing the number of events by T ensures comparing PCF for different evacuation times. The higher PCF, the higher the risk.

In particular, F95, T95, C, C+NE, and PCF are consistent with the KPIs selected in D4.2.2, Section 3.

In addition, maps concerning the final position of NE, the point of most probable contacts (due to PCF-related events) and the evacuation trajectories are show for some selected BET conditions, being representative of the whole sample. For earthquake simulation, the final users' positions are also shown to detect possible gathering areas which are not considered in the model.

### 2.3 Output comparisons criteria

The simulation output comparison is offered by separating the two SUOD conditions. Hence, considering each of the parameters in Section 2.2, earthquake and terrorist acts scenarios are separately compared taking into account:

A. the same SUOD conditions (e.g. no damage, intermediate damage, collapse for earthquakes; types of attacks in terrorist acts) to assess if the severity of the SUOD automatically implies an increase in risk;
B. the variations in the BET due to the presence of the different outdoor layout conditions, dividing types A from types B (and BET 4C plus BET 5, that is without and special building);
C. the same layout conditions in the different BETs, by focusing on the BET type A when present, which implies an higher exposure due to the special building presence;

Percentage differences between the baseline conditions are then calculated. The baselines are, respectively (letters correspond to the ones of the list above):

A. the no damage and the false alarm scenario
B. the layout with the central monument as the most free-of-obstacles scenario
C. the BET 3 conditions as the most simplest ones in morphological terms

Finally, only for the BET2, as the more representative in the project in view of multi-risk and connection with training tasks and case study (see WP6-D6.2.1), simulations without SLOD inclusion have been performed thus verifying which are the

## 3. Results

This chapter compares the data obtained from the completed simulations: considering the three different earthquake (Section 3.1) and terrorist attack (Section 3.2) scenarios with the different configurations of obstacles in the BETs.

### 3.1 Earthquake simulations

For each BET, regardless of the layout, Figure 9 shows a general overview of the evacuation process, by correlating the percentage of evacuees who arrived in a safe area [%], and T95 [s], considering the earthquake evacuation process (regardless of the damage scenario conditions) under initial heatwaves conditions. In particular, Figure 9-A traces the pairs, while Figure 9-B and Figure 9-C respectively traces the BET-related boxplot of arrived users' percentage and of T95. Figure 10 also consider the number of evacuees as a disclosed variable, in respect of T95, so as to outline the quantity of users in terms of 95$^{th}$ percentile of arrived evacuees.

T95 is lower for the BETs having a regular form (e.g. BET3) or a limited dimension (BET4), as expected. Then, BETs without a Special Buildings shows lower T95, as expected. Higher the BET area, higher the number of participating users, and then the number of arrived evacuees, except for BET5. The evacuation process in this case is highly affected by the outdoor layout, which is mostly occupied by green areas that are considered as not useable by pedestrians. Thus, the arrived users' percentage is the smallest one because most of users where not able to find a final safe position in the center of the square, due to the crowding of users towards it the progressive occupancy of areas closers to the square perimeter. In this sense, Figure 11 shows a comparison of BET2 (as representative of the other BETs) and BET5 final gathering areas and evacuees' paths at the end of the simulation.

BET 1 and BET 5 also high, which is affected by a not regular and symmetrical morphology in combination with ground slope that can slow down the evacuation process. The Differences in T95 between the points of the same BET are due to the combined effects of damage conditions and layout. Finally, BET5 offers an interesting.

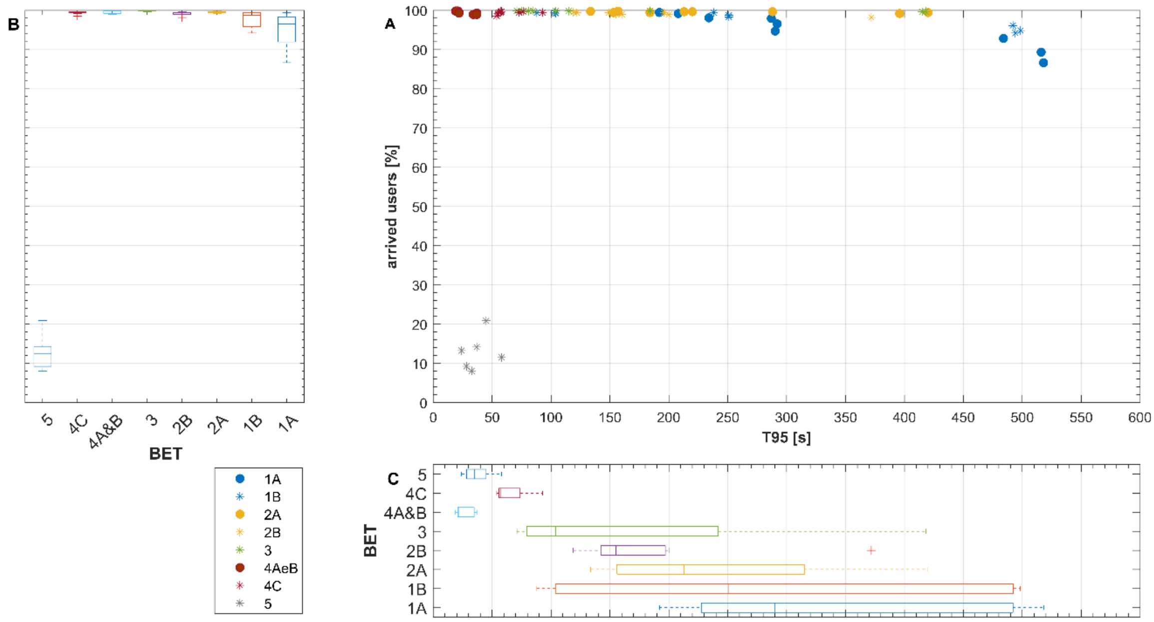



*Figure 9. Simulation data on T95 and the percentage of arrived evacuees in a safe area in respect to the initial number of participants, depending on each BET condition, and regardless of the damage scenario. Pairs are shown in panel A, while panel B and C respectively offer the boxplot of arrived users' percentage and T95.*

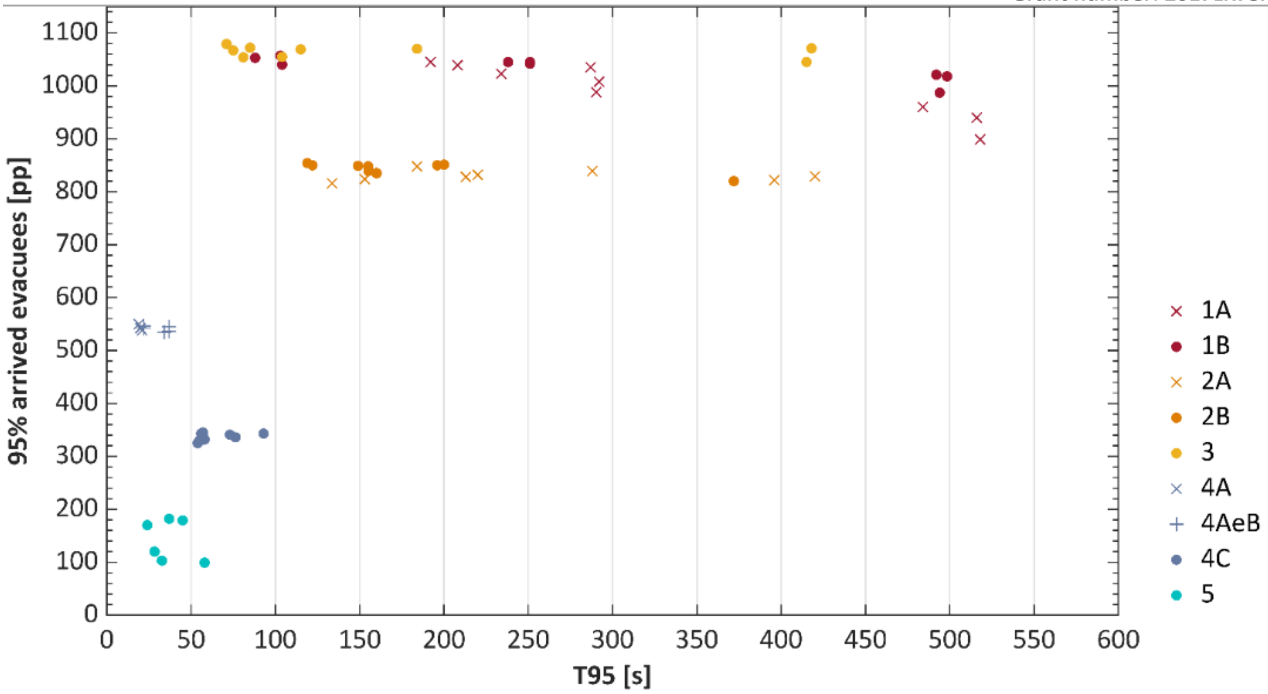



*Figure 10. Simulation-related pairs on T95-95th percentile of evacuees arrived in a safe area depending on each BET condition, and regardless of the damage scenario.*

In particular, for these analyses, user paths are considered starting from the edges of the square farthest from the safe zone, in order to represent the most critical condition. For a correct reading of the following figures, some aspects should be specified:

- black arrows - paths with a length of about 10 m ;
- red arrows - paths of 20 m or more in length ;
- green areas - safe zones, where users can safely stop.

For each Built Environment typologies the following considerations are made, which are expanded upon in subsequent sections through the observation of evacuation curves.
BET 4 in Figure 11 demonstrates rapid evacuation. The compact shape and modest size besides the limited number of people generated ensure proximity between the buildings facing the square and thus a short length of evacuation paths.

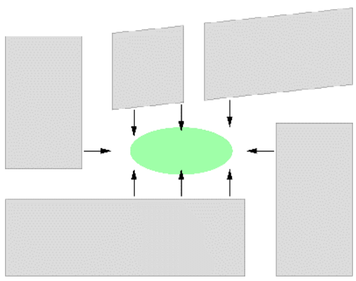


*Figure 11. Evacuation paths BET 4 (A-B-C)*

As it can be seen in the image, the evacuation path (black arrows) aimed at reaching the safe zone (green area), for all users at the edge of the square, is very short, regardless of their initial position.

Differently, BET 1 and BET 2, which are characterized by their elongated shape and large size, result in different evacuation time for users depending on their position.

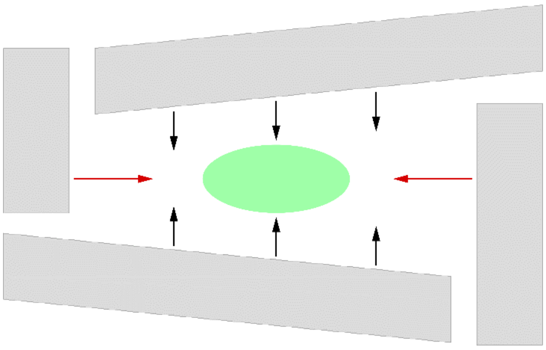


Figure 12. Evacuation paths BET 1 (A-B)

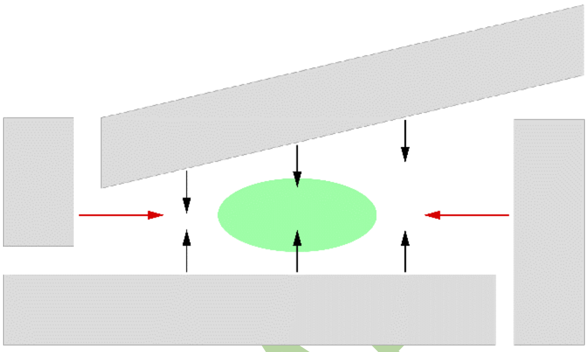


Figure 13. Evacuation paths BET 2(A-B)

In Figure 12 and Figure 13, it can be seen that evacuees who are originally located at the edges of the square have to take different types of routes. Evacuees located on the long sides of the square must travel a fairly short route, while those located on the shorter sides must travel a longer route to the center, taking a long time. From this derives an important observation, valid for understanding the pattern of the following evacuation curves for these BETs, which are characterized by a moderate slope in the first section and a gradual growth in the graph.
Similar behavior, to that just described, is found in BET 3.

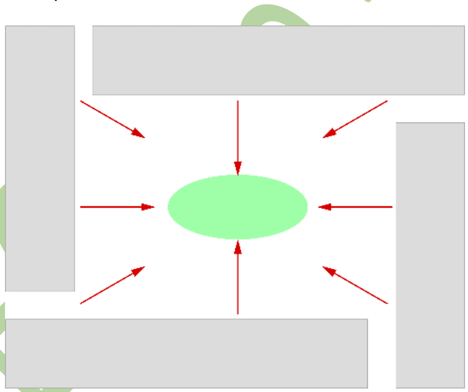


Figure 14. Evacuation paths BET 3

From Figure 14 it is clear that the regular shape that characterizes this type of built environment, determines a uniform distance of all buildings from the center of the square, where the safe zone is located. In addition, the large size of it causes this distance to be high, resulting in very long evacuation paths.
Finally, the large size of BET 5 (Figure 15) generates a large amount of users involved in the evacuation process. These users, however, do not have the possibility to all arrive in the safe zone within the time limit, due to the massive presence of green areas (i.e., garden not accessible to evacuees, e.g.: with high hedge at the boundary).

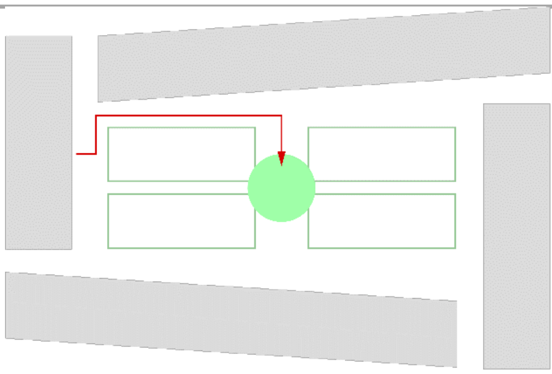


*Figure 15. Evacuation paths BET 5*

In fact, all evacuees who originally stand at the edges of the square, during their evacuation process, are impeded by these areas and forced to deviate their path to find an alternative road, free from obstructions. This change, beside slowing down the escape, increases the possibility of collisions and falls, as the space to move away from the buildings is limited compared to the effective area of the square (mainly occupied by the garden area, which is not accessible).

*Figure 16. Endposition map BET 5*

Figure 16, represents the distribution of users within the plaza at the end of the evacuation time. As can be seen, the people still moving within the BET (green spots with increasing density as the color intensity increases) are scattered throughout the plaza (outside the no-go zones). At the end of the evacuation, most of the users are not in the safe zone, located in the center, but are located near the garden area or the buildings, meaning in the areas with the highest risk of falling debris.
In summary, it can be said that for the same crowding conditions and inner layout elements (i.e., obstacles):

- Modest sizes of BETs imply proximity of the edges of the square to its center and thus shorter evacuation paths;
- Elongated shapes of the BETs define different evacuation path lengths, depending on the initial position of the users, thus varying the evacuation time depending on the morphology of the square.

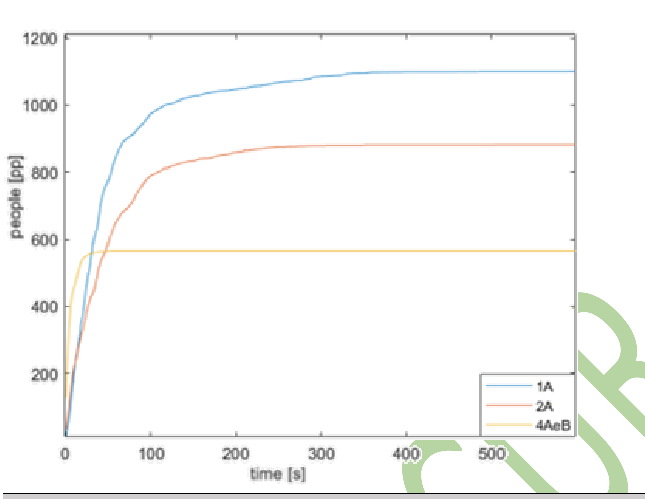
In the following, evacuation curves at the 50th percentile are compared. The graphs required for this level of analysis, are obtained through the Matlab plot, which allows the trend of the selected values to be plotted in a figure.

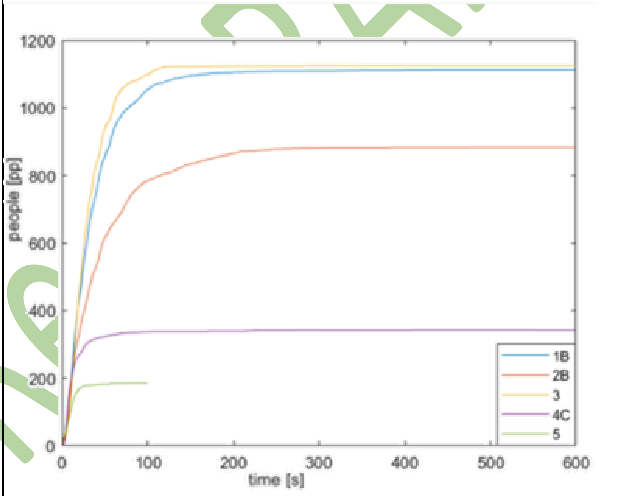
In line with the objective of the research, the factors considered for the analysis of the evacuation curves are as follows:

- People generated by the simulator as a function of the size of the BET under consideration;
- Debris caused by the earthquake that changes the behavior of the curves depending on the level of damage;
- Special Building affecting the behavior of the curves;
- How the behavior of the curves changes as the type of obstacle present changes.

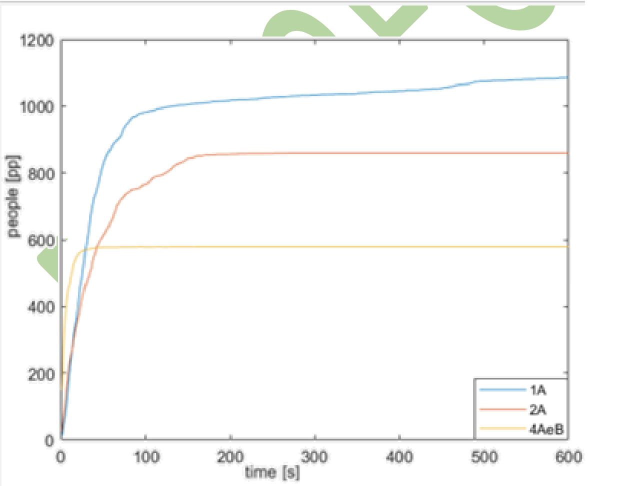
***No damage scenario (no blocked exits)***

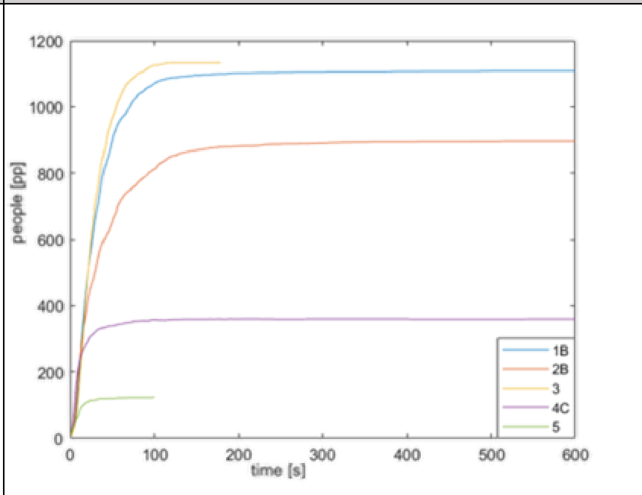
| BETs with Special Building | BETs without Special Building |
|---|---|
| Graphic 1: No monument | Graphic 4: No monument |




| | |
|---|---|
| Graphic 2: Only monument | Graphic 5: Only monument |




| | |
|---|---|
| Graphic 3: Poles and monument | Graphic 6: Poles and monument |

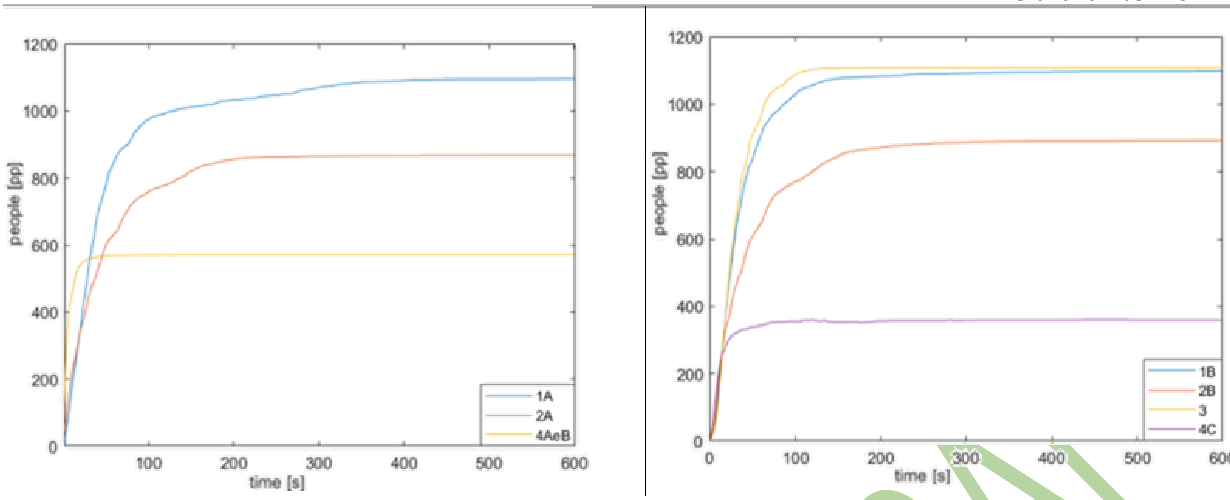
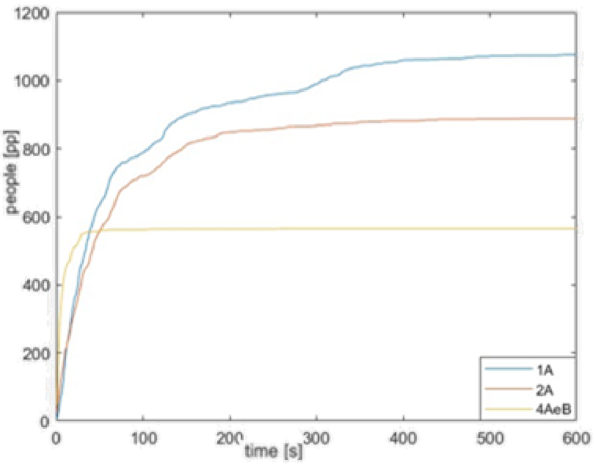


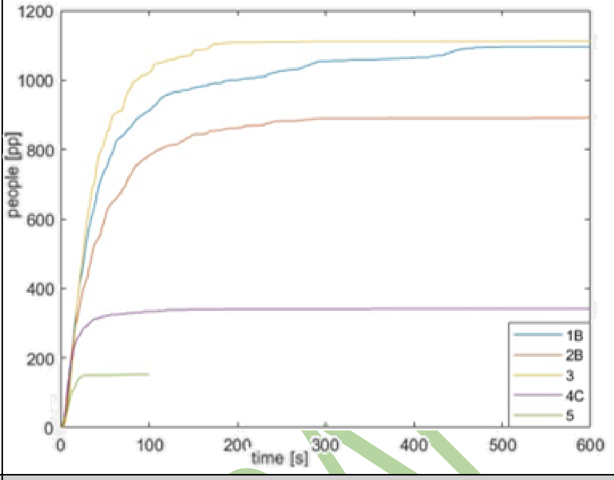

*Figure 17. Evacuation curves for each BET for the earthquake risk without damage*

All graphs are characterized by a steeply sloping initial section representing the initial stage of the evacuation process. For BET 4A and 4B, the first section is characterized by faster evacuation due to the small size that shortens the path for users to reach the safe area in the center of the BET. Subsequently, the curves tend to a horizontal trajectory.
In contrast, BETs without a Special Building exhibit an overlap of the first section. There is no Special Building, so the first section is less affected by the arrival of people who are already in the outer space. BETs 1B, 2B and 3 then tend to reach the horizontal trend in an interval of about 100 seconds while BETs 4A and 5 reach it only after the first 30 seconds.
Looking at the different geometric configurations, it is found that the slowest evacuation curves concern the *poles and monument* scenario. This highlights that the simultaneous presence of monument and poles is a feature that increases criticality, slowing down evacuation.
In contrast, the scenario that allows for faster evacuation is the one with the *only monument* configuration. The presence of the monument alone in the center of the square, shortens the evacuation route. In fact, the monument, placed in the center of the square and compact in shape, does not represent an obstacle but serves as a rallying point, around which evacuees position themselves at the end of the evacuation. The shape and size of the BETs affect the length of the path the user must travel from their starting position to the safe zone: central area of the plaza where they can safely stop.

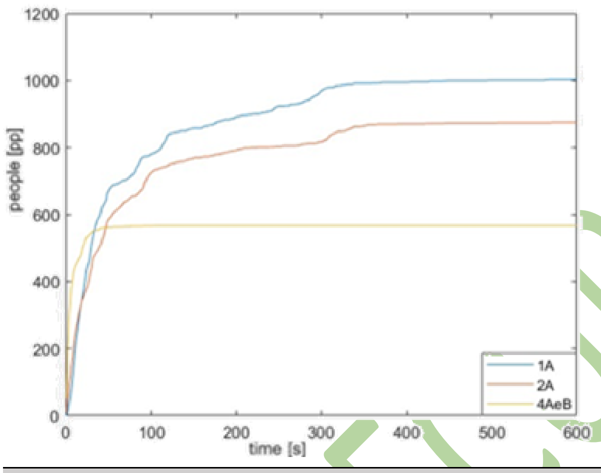
***Intermediate damage scenario (two blocked exits)***

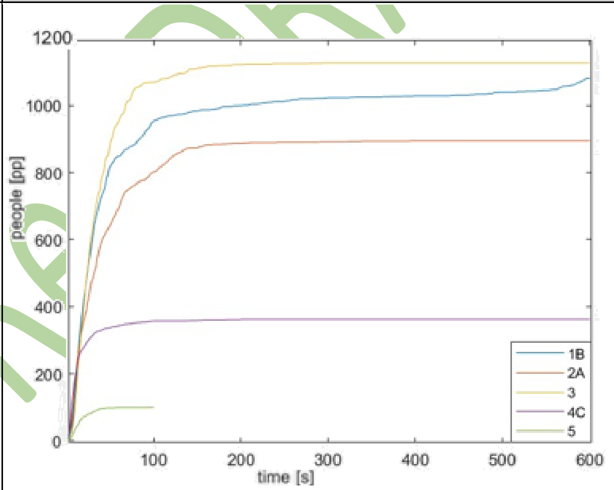
| BETs with Special Building | BETs without Special Building |
|---|---|
| Graphic 7: No monument | Graphic 10: No monument |



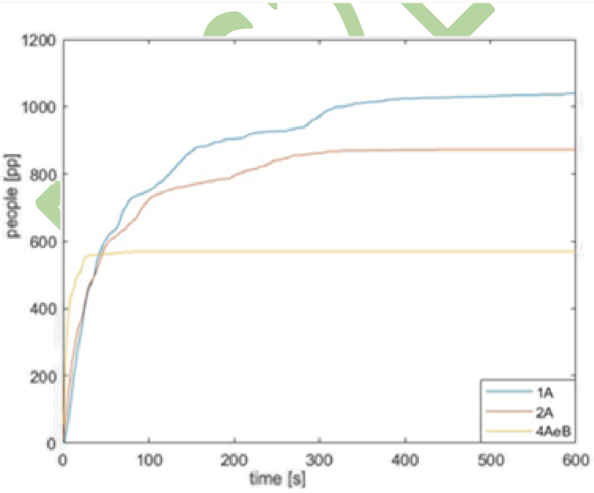




| Graphic 8: Only monument | Graphic 11: Only monument |
|---|---|




| Graphic 9: Poles and monument | Graphic 12: Poles and monument |
|---|---|



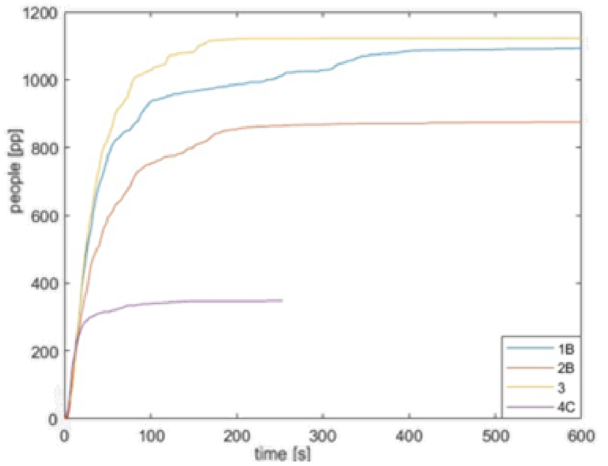




*Figure 18. Evacuation curves for each BET for the intermediate damage earthquake risk*

Qualitatively, the evacuation curves of the different scenarios, in the initial and final stages, assume the same reciprocal positions as the scenario without damage. In fact, under the same conditions, the trend is determined by the morphological characteristics which, being characterizing and intrinsic properties of the type of built environment, do not change in the different earthquake scenarios and their influence remains the same. Despite this, discordances can be found in the intermediate phase, in which collisions and changes in direction cause the graphs to oscillate differently.
In fact, the difference from the no-damage scenario, is the phase between the initial sloping line and the horizontal trend, which, in this case, occupies a larger time interval. In fact, in the intermediate phase, these graphs are all characterized by a discrete alternation of sloping and horizontal stretches.
This variable behavior of the curves is due to the presence of the debris in the square: these, in addition to representing obstacles, which evacuees must avoid, in fact diminish the cells available for exodus.

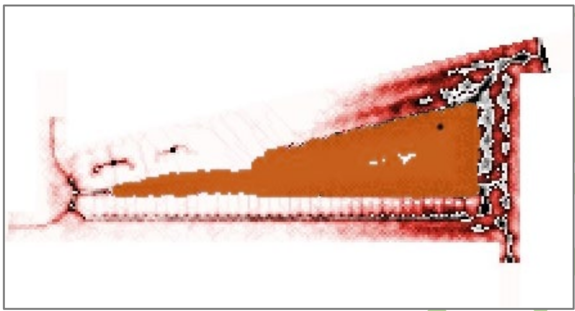


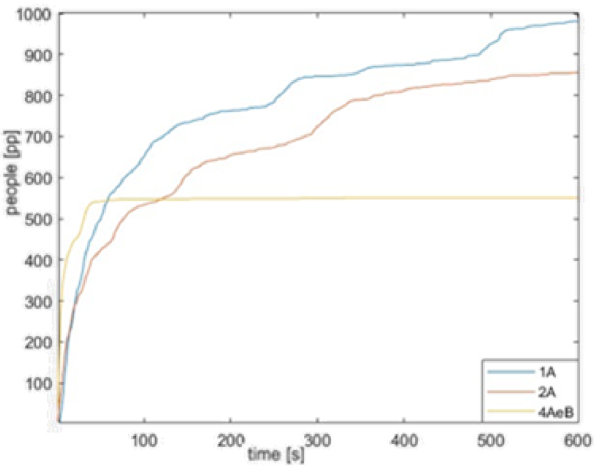
*Figure 19. Intermediate damage: example of Pathuse map (probability of space utilization for evacuee routes, in light red to black home) superimposed on seismicevac map (final gathering places of people in orange)*

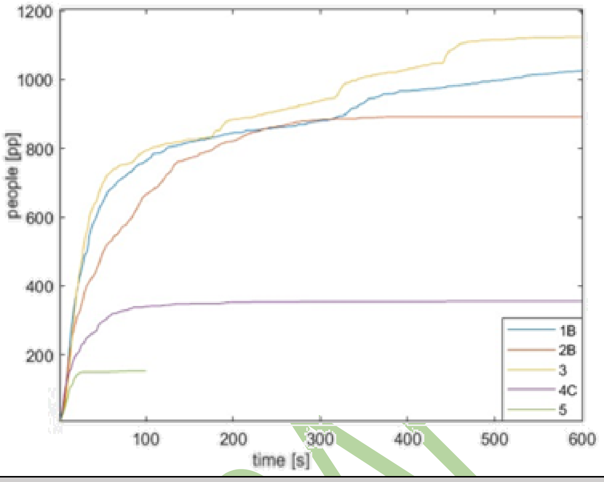
Figure 19 represents the concentration of users in the different cells: at the end of the evacuation, as can be seen from the orange color, the users present are all positioned near the right area due to the debris blocking the two exits on the left. In addition, users, during the evacuation process, tend to accumulate along the paths depending on the amount of rubble produced (see Figure 19 - map from light red to black). In the area on the right, the debris is quite dense, causing the evacuation flow to be organized along axial directions. Meanwhile, in the left side, access is wide and crowd motion less organized, leading evacuees even to collide, resulting in contact.

These phenomena, which result in moments of waiting (described in the graph by horizontal strokes), thus cause slowdowns to the evacuation process.
In relation to obstacles, the results for this earthquake scenario further confirm that the presence of the only central monument (*only monument* scenario) results in a faster exodus and that the simultaneous presence of poles and monuments results in a slower evacuation curve. As with morphological conditions, obstacles, given the same number of people generated, debris present and square morphology, have the same influence on evacuation.

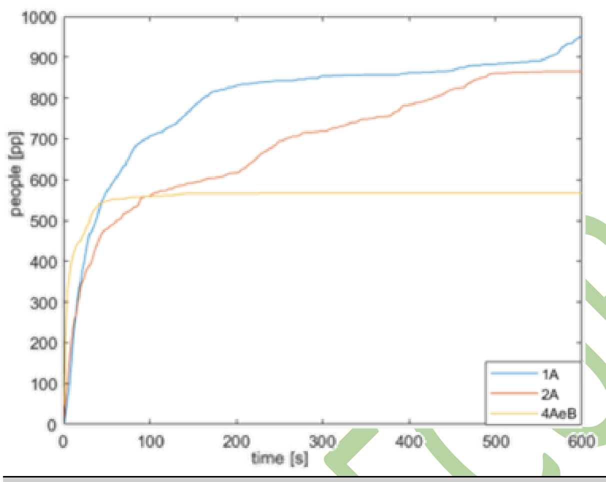
***Collapse condition scenario (all blocked exits)***

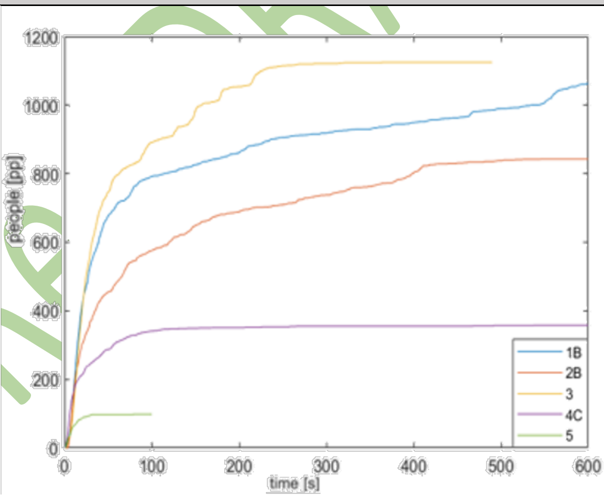
| BETs with Special Building | BETs without Special Building |
|---|---|
| Graphic 13: No monument | Graphic 16: No monument |



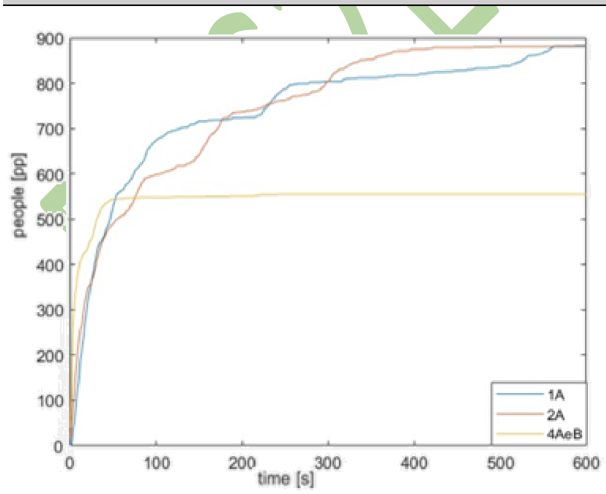




| Graphic 14: Only monument | Graphic 17: Only monument |
|---|---|




| Graphic 15: Poles and monument | Graphic 18: Poles and monument |
|---|---|



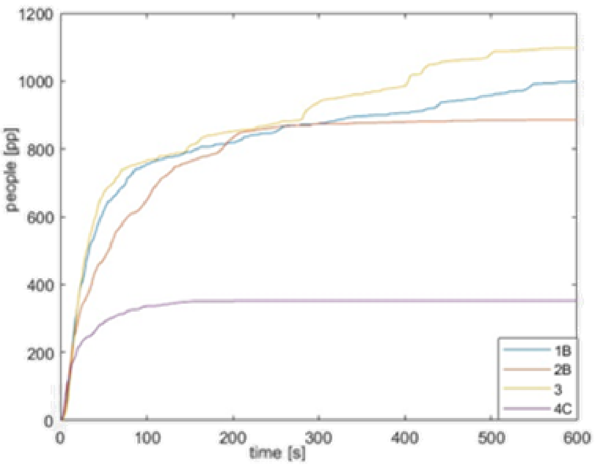




*Figure 20. Evacuation curves for each BET for the collapse condition for earthquake risk*

The slowdowns that occur in this damage scenario, due to contacts and falls, are represented in the graphs by the irregular trends of the curves, which generally take a long time to reach asymptotic behavior. In some cases, such as BET 1A in Figure 20, at the end of the 600-second simulation period, there are still users who are evacuating, and this graphically translates to a curve that ends in slope.
Furthermore, from the figures, it can be seen that although the evacuation curves maintain the same positions with each other, they behave quite differently from the reference scenario.
First, the slope of the initial section is generally smoothed out, the speed of the exodus also decreases in the first phase of the evacuation, due to the debris obstructing the users and making their path more articulated.
Below, the part of the graph composed of sloping and horizontal sections, which in the other scenarios characterized the intermediate phase of the process, in this one extends, for almost all cases, until the last 100 seconds of the simulation.
Behaviorally, this irregular pattern represented by continuous jumps in the curve results in a number of phenomena found, during the simulation, due to the accumulation of people in some areas of the square. Because there is so much debris, the space available to move is very limited (Figure 20), compared to the actual size of the BETs, and users are unable to head toward the center of the square in a linear direction, as in the no-damage scenario.

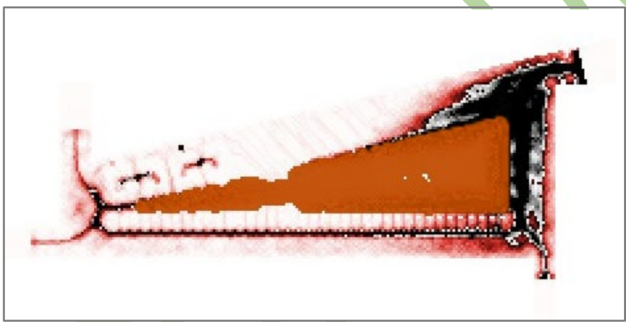


*Figure 21. Collapse condition: example of Pathuse map (probability of space utilization for evacuee routes, in light red to black home) superimposed on seismicevac map (final gathering places of people in orange)*

In fact, it occurs that evacuation times increase due to:

- The changes in direction, due to encountering obstacles (poles and debris) or the crowd blocking the passage, which lengthen evacuation routes;
- The moments of waiting (stops) caused by contact with other users and falls;

Horizontal segments thus stand for the intervals when no other users continue to reach the safe zone due to the above-mentioned slowdowns.

### 3.2 Terrorist acts simulations

Figure 22 traces the percentages of arrived users in respect of T95, so as to point out that most of the BETs can ensure the arrival of the evacuees towards a safe areas, regardless of the attack scenario, but compact and less crowded BET ensures slight lower evacuation times, as expected. Similarly, Figure 23 shows the evacuation performance of the BETs in terms of output pairs representing the T95 versus 95th percentile of evacuees arrived in a safe area. BETs with the special building (full dots) have a less scattered number of arrived evacuees.

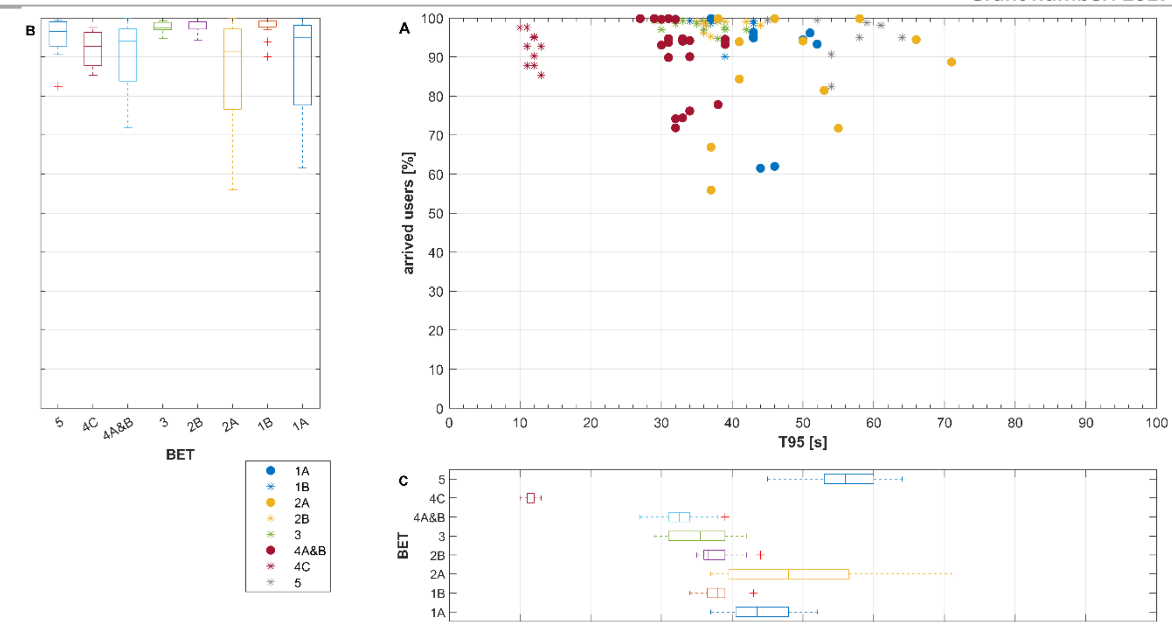



*Figure 22. Simulation data on T95 and the percentage of arrived evacuees in a safe area in respect to the initial number of participants, depending on each BET condition, and regardless of the attack typology. Pairs are shown in panel A, while panel B and C respectively offer the boxplot of arrived users' percentage and T95.*

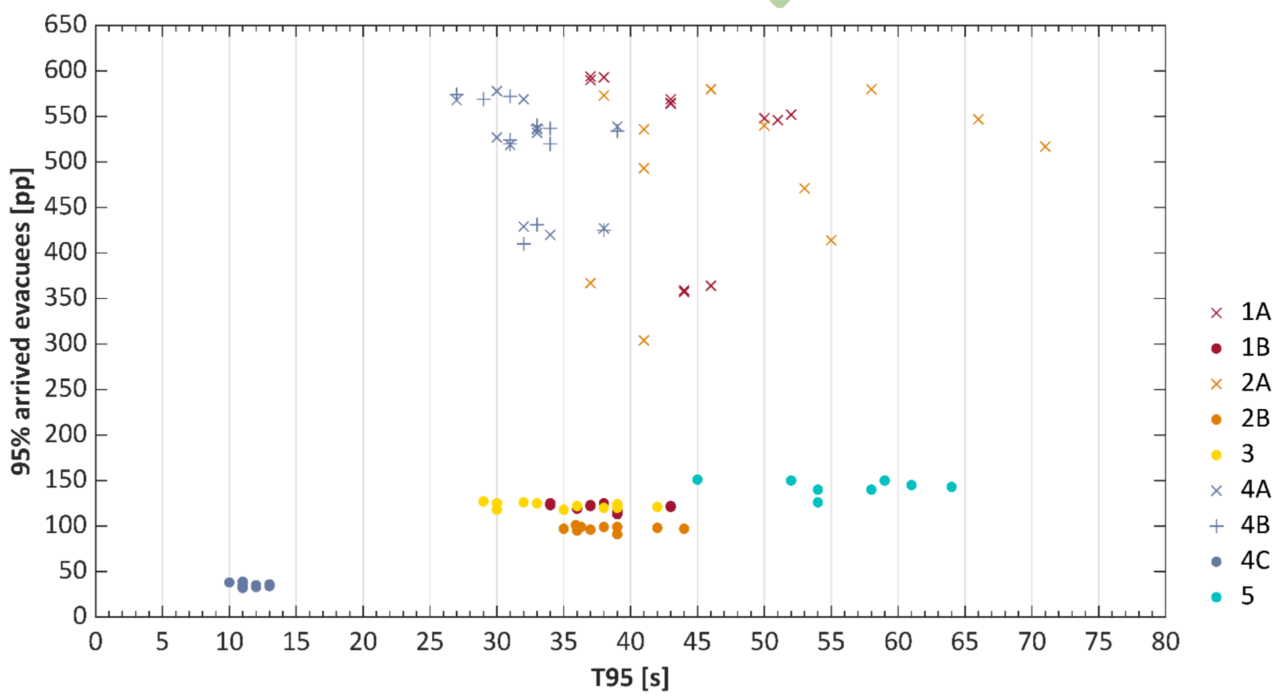
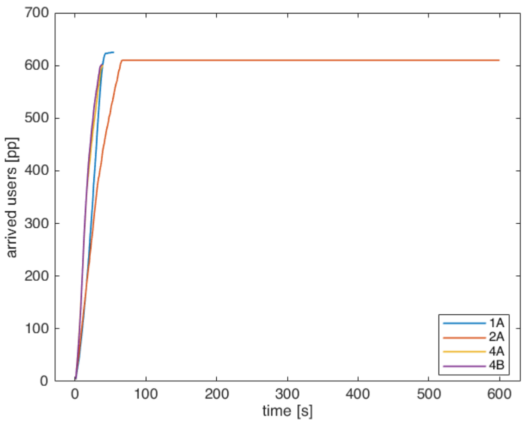
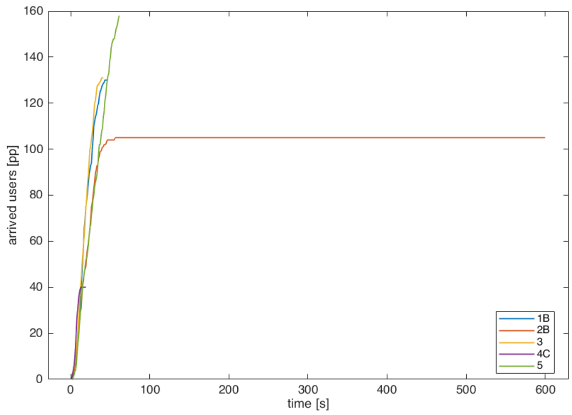
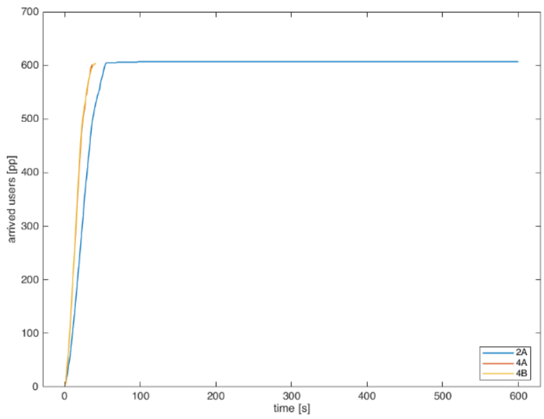
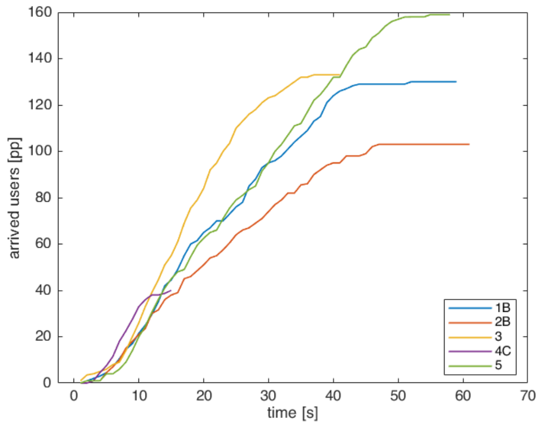



*Figure 23. Simulation-related pairs on T95-95$^{th}$ percentile of evacuees arrived in a safe area depending on each BET, and regardless of the attack and layout scenario.*

The rest of this Section compares the simulations performed, considering different types of attacks and different obstacle configurations. For all BET simulations without the special building, median crowding values are taken into account, while for BETs with the special building, the co-presence of people who are leaving the special building and users who are about to enter it are taken into account in addition to the normal median crowding conditions. It is worth noticing that additional analysis for the most significant BET with Special Building, i.e. 1A, 2A and 4A and 4B have been included in (Quagliarini et al. 2023a) to additionally trace the impact of different UTCI response of users before the terrorist act. In the following, the attention is mainly focused on the basic UTCI conditions as elaborated by D4.1.1 and adopted in terms of acceptability probability in D4.2.3 (see also (Cadena et al. 2023)).

***False alarm***

| BETs with Special Building | BETs without Special Building |
| --- | --- |
| Graphic: No monument | Graphic: No monument |
|  |  |
| Graphic: Only monument | Graphic: Only monument |
|  |  |
| Graphic: Poles and monument | Graphic: Poles and monument |

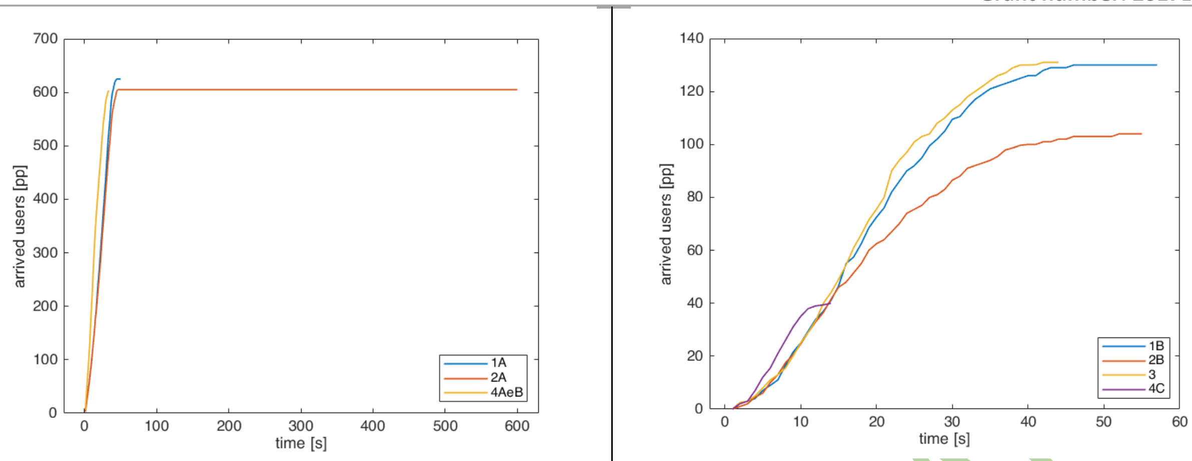


*Figure 24. Evacuation curves for each BET for the false alarm for terrorism risk*

Looking at the graphs, it is possible to observe that all evacuation curves are characterized by a significant slope in the first section, which tends to a horizontal line toward the end. This profile, similar to that recorded for seismic risk, testifies to a faster evacuation process in the initial phase.
Regarding the BETs with the Special Building, it can be seen that BETs 4A and 4B have almost identical trends and evacuation times (around 30 seconds), which are lower than the other types due to the small size of the space, for all geometric configurations. These also have a much higher 95th percentile flow of people than the others, as evidenced by the evacuation curves with a greater slope.
BET 2A, on the other hand, has a higher evacuation time, despite having fewer users involved than BET 1A. This is because at the beginning of the evacuation there is a greater confluence of people to the exits and thus less dispersion. Over time, areas of higher user density are created at the exit points, which decreases the evacuation flow, causing therefore, a slowdown in the exodus process. This phenomenon is more pronounced with regard to BET 2B, due to its highly asymmetrical configuration. Moreover, it has the highest number of (probable) falls among users, which is another cause of the slowing down of the exodus process.

Looking at Figure 25, which represents the places where users during the exodus process fall at least once, it can be seen that the falls are all concentrated in the lower right exit. This exit is the closest to the waiting area in front of the Special Building, and therefore the many people in it choose it as the first available option in the exodus, increasing the density along the same spaces.

For BETs without the Special Building, the number of users involved is small compared to the area of occupancy of the square, so naturally falls are absent, given the dispersion of people within it. This aspect results in greater heterogeneity among the evacuation curves of the various BETs.
BET 3, despite having the same number of evacuees participating in the evacuation process as BET 1B, and more than BET 2B has a shorter evacuation time than the other two. This is due to its more compact conformation.
BET 5 represents the configuration with the longest evacuation time among those without Special Building.

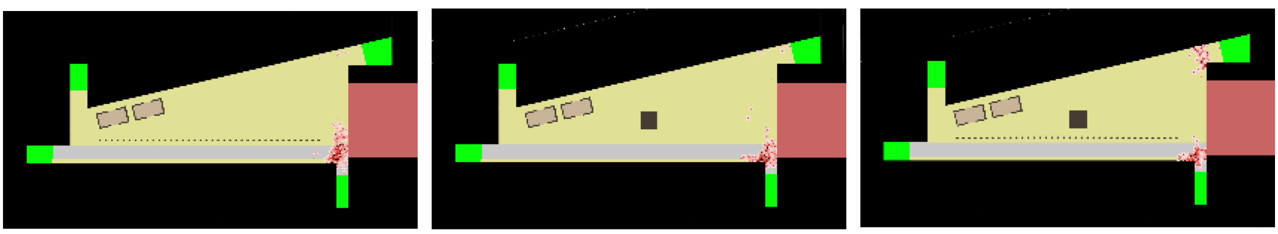
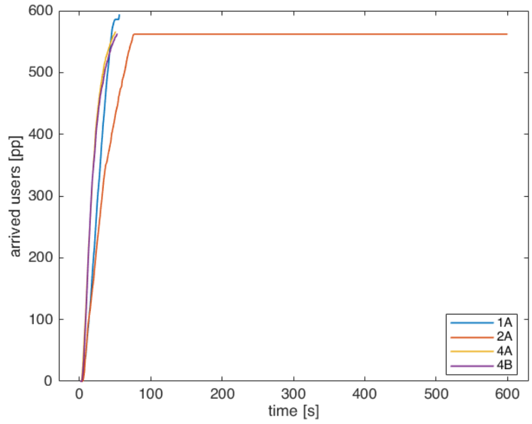
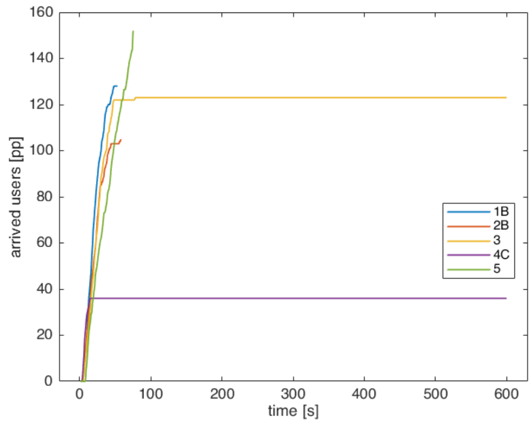
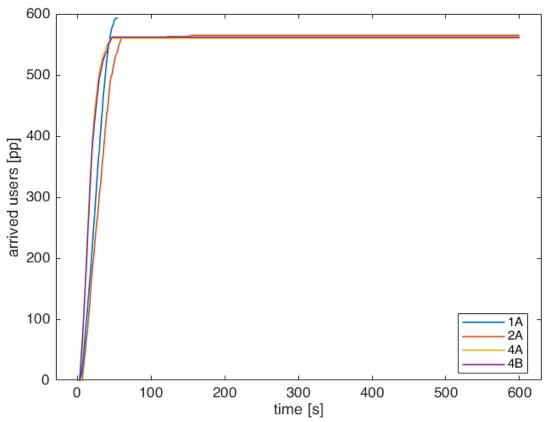
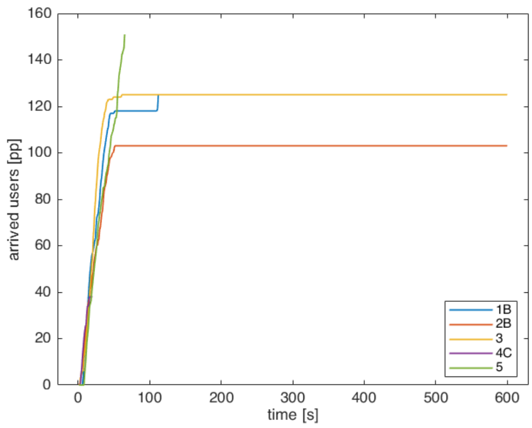


*Figure 25. bmp image. Falltot BET 2A Fals allarm for each geometric configuration. From left: no monuments, only monument, poles and monumet*

***Bombing attack***

| BETs with Special Building | BETs without Special Building |
|---|---|
| Graphic: No monument | Graphic: No monument |
|  |  |
| Graphic: Only monument | Graphic: Only monument |
|  |  |
| Graphic: Poles and monument | Graphic: Poles and monument |

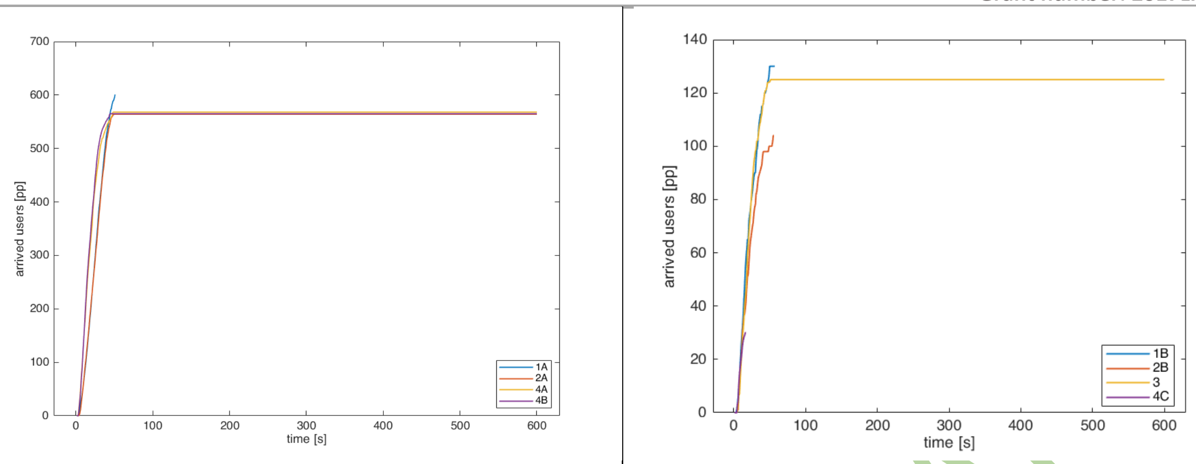



*Figure 26. Evacuation curves for each BET for the bombing attack for terrorism risk*

Similar to the false alarm scenario, BET 4 is the one with fewer people inside, so all things being equal compared to the others it will have a naturally shorter evacuation time.
BET 2A, has the highest evacuation time despite the smaller number of users involved compared to BET 1A. It also has the highest number of possible physical contacts and falls among users. Looking at Figure 27, which depicts the places where users during the exodus process fall at least once, we can see that the falls are all concentrated in the lower right exit, the one closest to the gathering in front of the special building, and consequently to a slowdown in the exodus process. The difference between the two BETs, is also marked by the considerable disparity between the two evacuation flows at the 95th percentile, and this can be observed from the graph, where the curve of 1A is much steeper than 2A.

In BETs without Special Building, the number of users involved is small relative to the area of occupancy of the square, so naturally the falls and the number of deaths and injuries is small, if not, in some cases, absent, given the dispersion of people within it. BET 5 with a higher number of dead or casualties users are the ones with the highest number of participants.

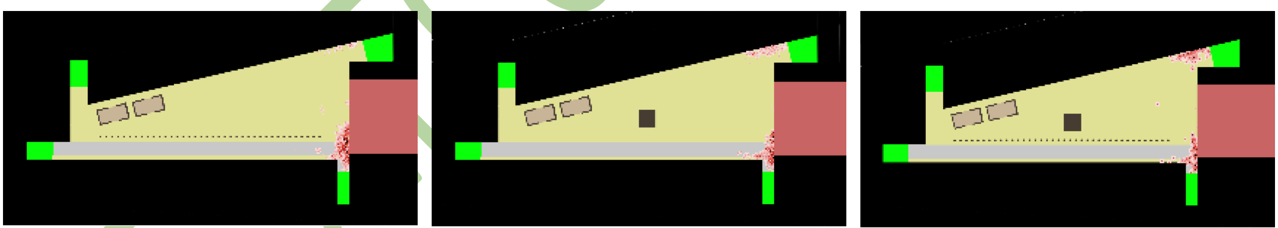
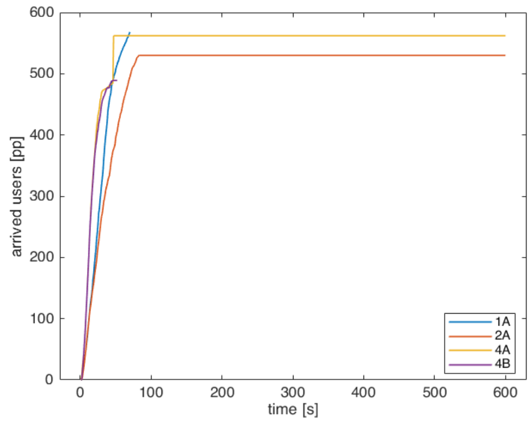
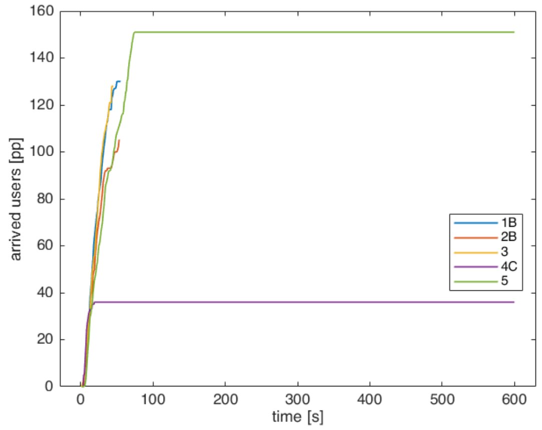


*Figure 27. bmp image. Falltot BET 2A Bombing attack for each geometric configuration. From left: no monuments, only monument, poles and monumet*

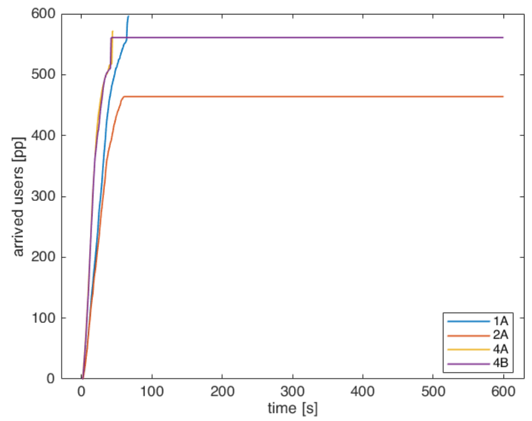
***Weapon attack***

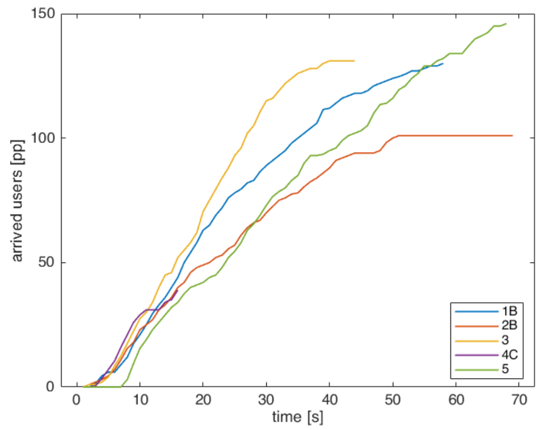
| BETs with Special Building | BETs without Special Building |
|---|---|
| Graphic: No monument | Graphic: No monument |



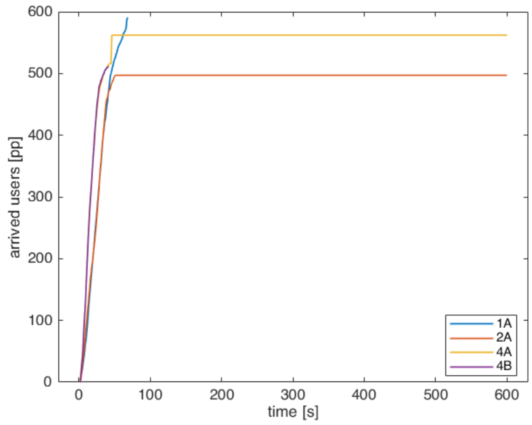




| Graphic: Only monument | Graphic: Only monument |
|---|---|




| Graphic: Poles and monument | Graphic: Poles and monument |
|---|---|



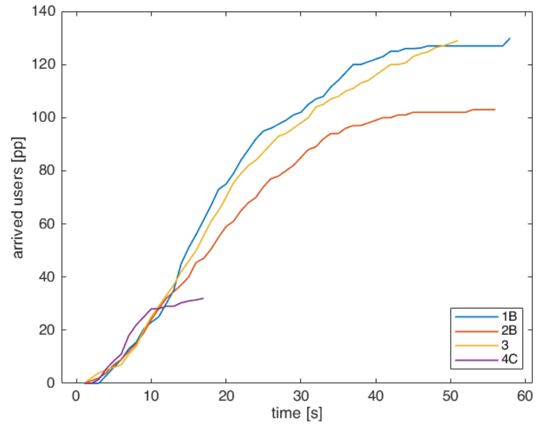




*Figure 28. Evacuation curves for each BET for the weapon attack for terrorism risk*

In general, a similar result to the previous conditions are obtained. It can be seen from Figure 28 that BET4C, is the one with fewer people in it, so all things being equal compared to the others it will have a naturally shorter evacuation time.

BET 1B, 2B and 3 have similar evacuation times at the 9th percentile. The difference between the three

BETs concerns the flow of people at the 95th percentile. Looking at the graph, it can be seen that at the initial instants the evacuation flow is similar among these, only with time the curve of 2B tends to move away assuming a lower 95th percentile evacuation flow value. While overall BETs 1B and 3, except for an intermediate part of the evacuation process, have very similar curve trends, in fact the two evacuation flows are very close. BET 5 and 5t, have a very similar trend. The small difference is caused by the UTCI conditions, so the different initial arrangement of users, as in the 5t which has the same morphology as the 5, there are trees, which cause this slight difference. In addition, we can add that these are the BETs with the longest evacuation time when comparing those without Special Building.
Regarding the comparison among BETs with Special Building, BET 2A has the longest evacuation time despite the smaller number of users involved.

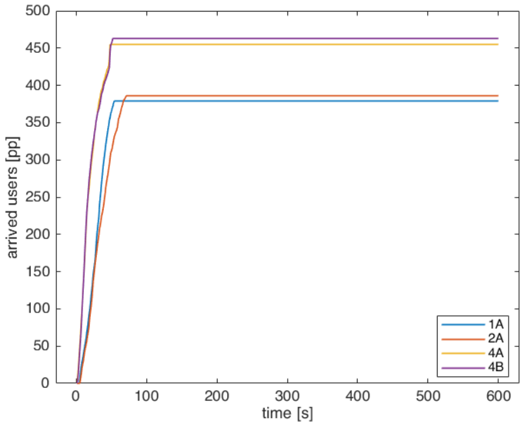
In BETs without Special Building, the number of users involved is small compared to the area of occupancy of the square, so naturally the falls and the number of deaths and injuries is small, if not, in some cases, absent, given the dispersion of people within it. BET 5 represents the configuration with the longest evacuation time among those without Special Building.

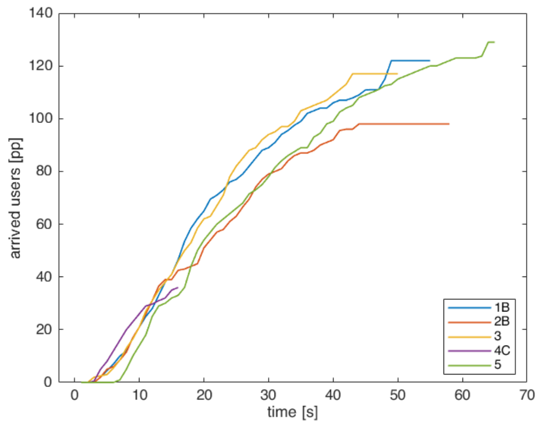
*Figure 29. bmp image. Falltot BET 2A Weapon attack for two geometric configurations. From left: no monument and poles and monumet*

***Vehicle running into the crowd***

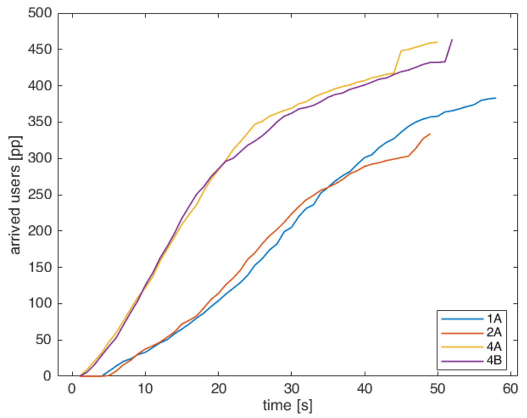
This type of attack generates a simulation in which a truck runs along a straight line at a given speed. In all the following simulations, compared with Bombing and Weapon attack, the number of fatalities is higher because the vehicle directly hits a larger portion of the crowd located exactly where there is maximum density, for example, by waiting at the entrance to the special building. However, the values of fatalities are taken in "excess": they could also be just wounded people who are unable to leave the square due to the effect of the attack.

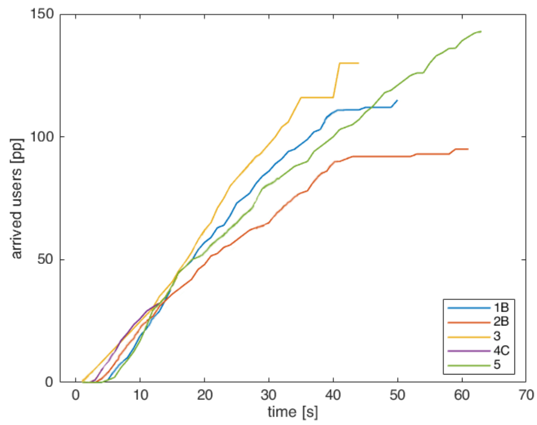
| BETs with Special Building | BETs without Special Building |
|---|---|
| Graphic: No monument | Graphic: No monument |



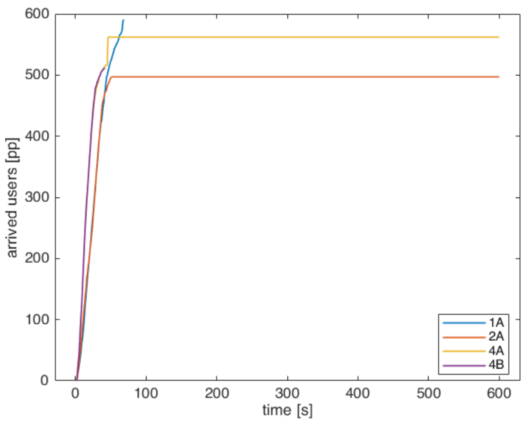




| Graphic: Only monument | Graphic: Only monument |
|---|---|




| Graphic: Poles and monument | Graphic: Poles and monument |
|---|---|



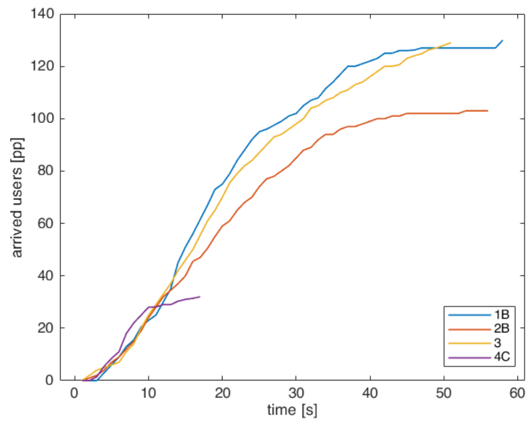




*Figure 30. Evacuation curves for each BET for vehicle running into the crowd attack for terrorism risk*

It should be made clear at once that the zig-zag pattern of the last part of the curves in Figure 30 is related to the variability of the outflow process determined by the presence of different types of paths. In particular, for BETs 1 and 2 that are very heterogeneous, the length of the paths taken by evacuees changes greatly depending on their initial location. The trend of the medians is calculated with respect to the

progressive sample, and thus we obtain such an overall trend. It can be seen from Figure 30 that BET4C is the one with fewer people in it, so all things being equal compared to the others it will have a naturally shorter evacuation time.
As for the comparison of BETs with Special Building, an almost identical trend is seen between BETs 4A and 4B. These have equal and lower evacuation times than the other types and a much higher 95th percentile flow of people than the others.
BET 2A has the longest evacuation time, despite the smaller number of users involved to that of BET 1A. This is due to the fact that BET 2A has a high number of probable user falls, as can be read by looking at Figure 31, which represents the places where users during the exodus process fall at least once. The falls are all concentrated in the lower right exits, and as a result, there is a slowdown in the exodus process.
In BETs without Special Building, the number of users involved is small compared to the area of occupancy of the square, so naturally the falls and the number of fatalities and casualties is small, if not absent, given the dispersion of people within it. The BETs with the largest value is BET 5.

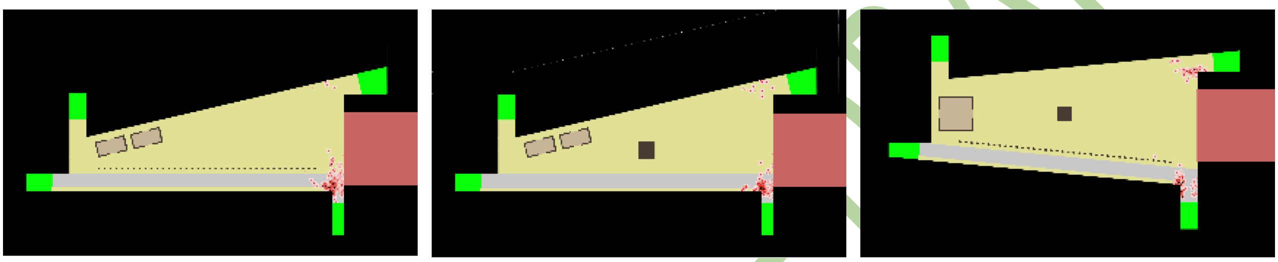


*Figure 31. bmp image. Falltot BET 2A Vehicle running into the crowd for geometric configuration. From left: no monuments, only monument; and Falltot BET 1A Vehicle running into the crowd for poles and monument configuration*

### 4. Conclusions and remarks

The results of the simulations clearly express the behavior of users in response to the seismic or terrorist event, investigating different types of built environment, in relation to climatic conditions (UTCI) and the presence of possible obstacles.

The analysis, carried out by comparing evacuation curves and data that briefly describe the exodus process, is thus aimed at identifying the influence that morphological and exposure factors have on the risk of BETs. From the considerations extracted from the results, the riskiest type of built environment for this multi-hazard scenario is then determined.

In summary, what emerged from the study is the close correlation between the risk faced by users and the morphology of the space in which they are located. In fact, the sizes and shapes of the squares taken into analysis highlighted the great difference between evacuation processes in small and compact BETs, with short and linear trajectories, and evacuation processes in BETs with irregular and extended geometries, with long and convoluted trajectories that adapt to the available space (thus including obstacles and potential debris) and the presence of other people in motion.

Simulation results also support the application of Key performance indicators especially for SUODs analysis, since the model allows to represent issues related to the evacuation process. Thus, the simulation outputs are also used to calculate the indicators values in current conditions as shown in D4.2.3 and D4.2.4 for the final metric values.

From a greater perspective, the results help to assume greater risk awareness and preparedness at different levels: users-community (activate the right actions), professionals (building-scale emergency planning), public administration professionals (large-scale emergency planning).

In particular, safety assessment and design of mitigation solutions for built spaces, in case of SUOD risk combined with square use conditions during critical temperature conditions, can make use of these results. The identification of the factors' influences on the evacuation process suggests the identification of real BE, which involve more critical safety conditions: having at hand the properties of the built space that most endanger users, the search for Italian squares characterized by them becomes quick and expeditious.
In this way, it is possible to assess risk on a typological basis, and direct the construction of built environments in the future toward choices that are more functional to such emergencies.
In addition, using the simulation approach used in this study, it is also possible to deepen the risk assessment for the identified "critical" cases, to verify how the conditions of ideal cases are more or less adherent than the real ones.
Therefore, given the focus on the impact of the morphology of BETs on the evacuation process, considering individual exposure and vulnerability as fixed elements of comparison in the simulations, future studies in this regard will have to analyze how different conditions referring to users alter the overall risk level.

For each case study, it is then possible to design and subsequently make risk mitigation solutions, related to the reduction of the vulnerability of the structures as well as the organization of the various obstacles in the plaza itself to facilitate the outflow and collection of evacuees in case of an emergency.

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