(make) Built Environment Safer in Slow and Emergency Conditions through behavioUral assessed/designed Resilient solutions

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WP1–BE and SUOD: State of the Art (SoA), risks and human behavior

T1.3 Terroristic acts (SUOD) in BE: SoA with identification of conditions/factors (in outdoor BE) influencing the risk. Current mitigation strategies analysis. Definition of human behavior including crowding conditions by combining SoA data and real-world events analysis

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Abstract

Terrorist attacks in the last decades have contributed to reduce considerably citizen safety in the Built Environment. In order to develop risk-mitigation strategies, the human behaviours (intended as individual's and crowd's reactions to such sudden disasters) must be deeply inquired. Comprehending recurring behaviours and predicting possible individuals' choices can be useful to determine which factors (e.g.: the type of attack, overcrowding levels, users' typologies) and environmental conditions can aggravate an emergency situation. To this end, the present work takes advantages of results of research works on previous real-case observation, based on real-world videotapes (i.e. in European Countries). Qualitative investigations and related statistical analysis from previous reference works are summarized to reveal which are the more frequent human behaviour observed in the inquired terrorist events. The quantitative analysis are organized to describe individuals' motion in the evacuation. Comparisons with previous database concerning other disaster typologies (e.g.: earthquakes, fires and floods) are performed to evaluate differences in adopted behaviors and motion quantities. Results from reference work show that differences among terrorist acts behaivours and those related to other kind of emergencies exist, thus remarking the importance of emergency-related database in the risk assessment process. Database creation constitutes a starting point to be reused in the future work packages with the aim of providing input data for evacuation simulations.

Keywords

Human behaviours; terrorist acts; real videos evacuation; qualitative analysis; quantitative analysis; database creation

Approvals

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Summary

1. Introduction

Terrorist acts in the Built Environment (BE) are characterized by a complex system of interactions between the attackers, the exposed individuals and the BE itself, as well as by the effects of a no-notice emergency (Sudden onset) event on the individuals (Golshani et al. 2019), as previously outlined in D1.3.1 (e.g. compare to Section 4 and 5) and D1.3.2 (e.g. compare to Section 3). Evacuees' behaviour and the definition of its rules constitute an essential issue to be studied in order to improve our knowledge on such emergency management (Bernardini et al. 2019). In fact, a key aspect in proposing and evaluating safety measures, emergency management solutions and risk reduction interventions is to considerate the "human factor" in the emergency scenarios definition. Such needs have been also underlined in D1.3.2, Section 4.

To this end, efforts to provide databases reporting qualitative and quantitative data on evacuees' behaviours should be performed (Haghani and Sarvi 2018). Table 1 resumes main qualitative and quantitative data collected from previous works to characterize these phases and the related evacuees' behaviours in the emergency, by evidencing common issues, quantities and evacuation data between all the different kinds of disasters (Kobes et al. 2010; Bernardini et al. 2016; Lin et al. 2020; Zhu et al. 2020). Regardless of the specific emergency event occurred, they can be organized by distinguishing 3 main and common evacuation phases (Alexander 1990; Kobes et al. 2010; Bañgate et al. 2017): a pre-movement phase, which essentially deals with the identification of the emergency conditions (including alarm/alert) and with preliminary actions towards the evacuation motion; a motion phase (that constitute the evacuation itself); and finally a post-evacuation phase, in which people are "in safe conditions" and try (if possible) to overcome the disaster event. Nevertheless (qualitative and quantitative) differences among evacuation kinds exist and could affect the final process (Bernardini et al. 2019; Lin et al. 2020; Zhu et al. 2020). The level of knowledge of specific emergency-related issues affects the possibility to represent the evacuation scenario in a proper way. Hence, since, such elements can be used to delineate effective guidelines for emergency planning and for the development of simulation tools that support designers in risk scenarios creation (Caira et al. 2017), efforts to improve the description of human beavers in the different emergency scenarios should be carried out in a priority way.

In view of the above, this introduction highlights common issues concerning the "human factor" in emergency scenarios (Section 1.1) and then traces the lacks related to terrorist acts while addressing the aim of this report (Section 1.2).

Table 1. Data for evacuation characterization according to previous works collected by (D'Orazio and Bernardini 2014)

Evacuation data	Type (main unit of measure)	Short description
Delay times	Quantitative (s)	Time of reaction to the event; pre-movement time characterization
Walking speeds	Quantitative (m/s)	In different conditions of crowdedness and path
Occupant characteristics	Quantitative and qualitative	Differences in actions, reactions, specific parameters
Evacuation behaviours	Qualitative	Series of action during evacuations
Evacuation path obstruction	Quantitative (e.g.: density [person/m²]) and qualitative	Influence of environmental conditions on queue delays or block egress
Exit and path choice decisions	Quantitative (e.g.: flow [person/s]) and qualitative	Influence of environmental conditions and other people position on travel paths and travel times

1.1. Common issues in emergency conditions: an overview on the state of the art

Qualitative investigations concerns the behaviours adopted by the evacuees during the emergency process, that is by analysing the step-by-step actions carried out by individuals, also in relation to their statistical significance (Helbing et al. 2002; Yang et al. 2011).

It is worthy of notice that human behaviour and choices in the whole emergency condition-prone process seem to be generally characterised by the impact of the survival instinct and the protective sense toward bonded people, as well as affected by the need of quick response in emergency (Pietrantoni and Prati 2003).

In front of a hazardous situation, an individual can react with a fear sensation that can constitute a warranty to the survival, since he/she tends to activate reflexes able to save his/her own life (e.g. by activating individualistic, or rather "selfish" and competitive behaviours) (Drury and Cocking 2007; Yang et al. 2016; Haghani and Sarvi 2018). Differently, feels of anguish, that emerge when it is not clear the risk to face off, could lead to a "panic" condition in presence of four factors, according to a classical perspective on such issue (Santoianni, 2000): 1) diffused anxiety before the disaster; 2) lack of the presence of a leader that can guide the crowd in an eventual evacuation; 3) the perception to be trapped in the only available escape route; 4) and finally the appearance of a factor that could accelerate the panic itself (e.g. in case of bombing, the sounds of the explosion or the smokes due to it). In such situations, pro-social and altruist feeling can be easily recognized. In the terrorist attack to the metropolitan lines of London in 2005, people perform their evacuation in an "self-organized" manner supporting people with difficulties, without any competitions (Drury and Cocking 2007; von Sivers et al. 2016). In this sense, other studies on "panic" demonstrated how a state of anxiety among evacuees allow performing adaptive behaviour during the escape (Alexander 1990; Mawson 2012). In other events (e.g.: earthquakes), "panic" conditions have been observed but for a restricted period of time (about some dozens of seconds) (Pietrantoni and Prati 2003), and could lead to helpless levels in respect to the surrounding BE conditions, by also provoking the interruption of the evacuation process nearby the initial position in the BE (e.g., out of the building in which the individual is initially placed) (Bernardini et al. 2019).

Besides "panic", researches shown how the first cause of the incidents/casualties (e.g.: trapped and injured people) in disaster-induced evacuation is the evacuation delay (Pietrantoni and Prati 2003) rather than a "panic" situation that occurs less frequent according to the simultaneous manifestation of aforementioned four factors. The delay (which can be described from a quantitative point of view, compare to Table 1) (Lovreglio et al. 2019) can be caused by imprecise information reached by individuals: people tend to minimize the risk perception dilatating the evacuation times (Drabek 1999). This delay is associated to the pre-movement phase, when the time between the alarm and the starting of the evacuation is a function of several factors (e.g. environment typology, performed activities by the evacuees) (Purser and Bensilum 2001; Shi et al. 2009; D'Orazio and Bernardini 2014) Anyway, during this phase, people do not keep paralyzed but, on the contrary, their reaction is active-type, manifesting reactions as the *"attachment to belongings"* and to other people (Kobes et al. 2010; D'Orazio and Bernardini 2014; Bañgate et al. 2017) widely observed for many emergency sources. In case of fire, the familiarity with spaces plays a key role on the reaction time. For instance, in their own dwelling, individuals' reaction time generally increases, since people are discouraged to leave their properties and take time to collect belongings. Additionally, in familiar places, the occupants tent to perceive a better safety perception, which can discourage them to start the evacuation process (i.e. leaving the initial position to reach a safer area) (Pietrantoni and Prati 2003).

Regardless of the emergency-related conditions, the presence of social-based and attachment-related phenomena, as well as the need of situational updates about the emergency state generally occurs also after the pre-movement phase(Averill et al. 2005; Kobes et al. 2010; Bañgate et al. 2017; Bernardini et al. 2019), when the evacuation starts, and people's motion is activated by the attraction towards safe areas (Helbing and Farkas 2002). Social bonds heavily influence this phase as well: people sharing relationships can support reciprocally, and, from another perspective, their evacuation time could significantly increase while awaiting one to each other (Mawson 2007). This behaviours can be amplified also between individuals who share the same evacuation target, in a cooperative behaviour approach (Cheng and Zheng 2019), by additionally leading to the so-called "herd behaviour" (Helbing and Farkas 2002; Raafat et al. 2009; Bernardini et al. 2019). In case of overcrowding conditions, evacuees can reciprocally be influenced in the motion speed generating "stop and go" waves (Helbing and Johansson 2012), as well as by the "faster-is-slower" effect (people try to move with the aim to looking for free spaces in the BE, while queueing or while deciding the evacuation paths, and so they fulfil such spaces and slow/down or even block the evacuation process) (Gu et al. 2016). Finally, in each emergency condition, the goodness of the evacuation process can be reasonably improved in presence of a guide or a "leader" that is a person in charge to support the evacuees as well as to assist individuals in difficulties (Okaya and Takahashi 2013). A "Leader" is generally associated to a recognizable member of the BE management staff/of the rescuers' teams/of Law Enforcement Agencies, or he/she can spontaneously appear in the crowd (an evacuee, due to self-organizing issues in crowd/group motion). Especially in the first case, his/her presence can increase the coordination between the evacuees thus leading towards the improvement of the evacuation motion conditions (Raphael 2005; Fang et al. 2016; Gayathri et al. 2017; Bernardini et al. 2019).

Besides such qualitative aspects in the emergency process (i.e. behaviours and actions, including recommended behaviours and guidance of leaders'/rescuers' instructions) (Bañgate et al. 2017; Bernardini et al. 2019), the quantitative motion analyses are essentially to correctly assess how "safe" is a Built Environment (BE) in respect to the users' response to the disaster. They involve the description of motion parameters over time/space and depending on surrounding conditions (e.g.: people density, individuals' parameter on motion such as the velocity, travelled paths and evacuation flow). Such analyses are preferably performed through an accurate investigation of real evacuation videotapes (Ronchi et al. 2014; D'Orazio et al. 2014b) by using different motion tracing techniques. One of the motion quantities that higher affect the motion of individuals is the crowd density: certain low-density of people their motion into a confined space can be reconducted to the gas behaviour, and for high density to fluids ones according to (Helbing & Farkas, 2002). Such analogy reveals the necessity to define the levels of pedestrians' density in relation to a space area. The "Level of Service" (LOS) is introduced in 1971 by Fruin to measure the grade of pedestrian traffic volume in terms of people density (Fruin 1971). Each LOS level is generally provided with a mean velocity range of values [m/s] and with a density range of values [m²/person], both for normal walking and evacuation conditions (Klüpfel and Meyer-König 2014). The fluid-dynamic analogy at a macroscopic level allows representing these phenomena (pedestrian flow and the mechanics of fluids) with the same physical quantities (Lighthill and Whitham 1955): the specific flow (q [person/s]), the velocity (v [m/s]) and the density (k [person/m], according to original source). At the stationary state, these three measures are calculated as in equation (1), that is named "equation of state":

$$q = k * v \tag{1}$$

The equation (1) permits to generate the fundamental diagrams that describe the relation between flow and density (q-k) and velocity and density (v-k) (Johansson et al. 2008; Transportation Research Board 2011; Chen et al. 2012; Burghardt et al. 2013; Bosina and Weidmann 2017). From the v-k diagram, it is observed the velocity trend in relation to the increase of the number of people in the scene. In the first part of the trend, the curve is quite constant, and at low density the velocity coincides with the pedestrians' preferred speed. With the increase of density, the mean velocity decreases and, for the maximum level of density, the velocity will tend to zero (the density, in any case, will reach a maximum value due to the area occupied by human bodies). the maximum q seems to depend on the specific kind of emergency as well as on the situational characteristics (e.g. smokes, indoor/outdoor, shape of the BE spaces of motion, pedestrians' engagement levels and motion conditions, e.g. normal/emergency evacuation motion) (Chen et al. 2012; Bernardini et al. 2016; Bosina and Weidmann 2017).

The q-k diagram describes the tendency of the flow in relation to the density: for low-density values, the flow increases linearly until it reaches is maximum value q_{max} that displays the maximum capacity of the chosen area. When the density increases over this point, the flow decreases until zero in correspondence to the maximum density value.

1.2. Current lacks in terrorist acts emergency assessment and aim of the work

Previous studies clearly investigated behavioural issues related reacted to terrorists, their organizations and other issues dealing with security (i.e. work) in large scale events (Freytag et al. 2011; Ruiz Estrada and Koutronas 2016; Tutun et al. 2017; US department of Homeland Security 2018; Marchment and Gill 2019; Fu et al. 2020), while general countermeasures to terrorist acts were developed (including regulations, as in D1.3.2, Section 3) also in relation to the different types of attacks that could be performed (National Consortium for the Study of Terrorism and Responses to Terrorism (START); Federal Emergency Management Agency 2009).

On the contrary, a limited number of studies deals with the assessment of "human factor" in terrorist acts-related emergencies, by mainly pointing out qualitative issues in motion and by using interviews to survivors or (more limitedly) videotapes of real world events (Averill et al. 2005; Bruyelle et al. 2014; Bernardini et al. 2017b; Li et al. 2017; Liu 2020). Unfortunately, such studies are mainly related only to indoor scenarios (terrorist acts in buildings). At today, and at the authors' knowledge, the main efforts towards an inclusive indoor-outdoor analysis and organization of emergency behaviours in only provided by the researchers at UNIVPM group (Bernardini and Quagliarini 2021), on which bases this deliverable has been developed. Some works provided first insights on human motion quantities, i.e. evacuation speeds and their fluctuations (range from about 0.2m/s to 1.6m/s) (Wang et al. 2019), but limited data are provided at today. Finally, a limited number of such works tries to provide insights on solutions to increase people safety against terrorist attacks based on data the nearer to reality (Bruyelle et al. 2014; Bernardini et al. 2017b; Bernardini and Quagliarini 2021).

On the contrary, many simulation models (including the effects of the terrorist acts itself) were developed in the past (Albores and Shaw 2008; Manley et al. 2016; Wang and Wang 2017; Chen et al. 2018), but most of them include general-purpose behaviours (e.g. those related to fire egress, also in view of effects due to the attack) and only few of them are based on effective evacuation scenario-related behaviours (Li et al. 2017; Liu 2020). Such modelling issues are based on microscopic approaches, due to the possibility to represent the interactions among attackers, attack actions and occupants over time and space (e.g. by pursuing a social-force based (Liu 2018, 2020) or a cellular automata (Chen et al. 2018) approach, also integrating Agent-based models (Şahin et al. 2019)).

Hence, efforts to provide reliable databases on terrorist acts-related emergencies is urgently needed (Liu et al. 2020). According to previous methodologies adopted in other kind of emergencies and based on the analysis of real evacuation events by videotapes (so as to have a potentially-unbiased data source, compare to D1.2.5, Section 1 and Section 2) (Bernardini et al. 2016, 2019; Haghani and Sarvi 2018), the present work aims to collect a quantitative and qualitative dataset basing on the results of (Bernardini and Quagliarini 2021), to provide a summary of the main evacuees' behaviour performed by evacuees in a terrorist attack (both focusing on indoor and outdoor spaces in the BE) and to comprehend the trend lines of principal quantities that describe the people's motion. The use of videotapes analysis by (Bernardini and Quagliarini 2021) is in line with other works on terrorist acts (Bernardini et al. 2017b; Li et al. 2017; Liu 2020), as well as considered as valid for the other types of emergencies (e.g. compare to D1.2.5, Section 2).

According to this work aim, similarly to D1.2.5-related activities, as well as basing on the recent UNIVPM researchers' outcomes (Bernardini and Quagliarini 2021), the deliverable is organized by resuming the methodologies to create the database, organizing it and analysing the evacuees' behaviours from qualitative and quantitative standpoints (Section **Errore. L'origine riferimento non è stata trovata.**). Then, results from previous studies are summarized by distinguishing qualitative (i.e. common and peculiar emergency behaviours) and quantitative (i.e. fundamental diagrams) aspects (Section **Errore. L'origine riferimento non è stata trovata.**), also in the view of comparing results with previous outcomes of other kind of emergency and of terrorist-related emergencies.

2. Research phases and methodology

Consolidated behavioral analysis criteria (Johansson et al. 2008; Bernardini et al. 2016, 2019; Haghani and Sarvi 2018; Zhou et al. 2018; Lu et al. 2019; Wang and Shen 2019) can be used to investigate different kinds of emergencies including terrorist attacks (Bernardini and Quagliarini 2021). They are based on the following steps

1. defining a database of real-world videotapes to investigate evacuees' behaviors in real terrorist attacks (Section 2.1);
2. detecting evacuation behaviours on the videotapes, by organizing them in a "behavioural database", by including the analysis of their statistical significance (Section 2.2);
3. assessing evacuation motion quantities from both an individual and a collective perspective (Section 2.3).

2.1. Characterization of the videotapes sample

According to the reference work considered in this deliverable (Bernardini and Quagliarini 2021) and the criteria shared by D1.2.5, he terrorist attacks database can be defined through a selection of real world events coming from different Countries, so as to improve the statistical significance of the results and limiting geographical and social issues in evacuation behaviours. Furthermore, the attacks should register relevant number of injured and victims thus demonstrating the impact of emergency conditions in the safety of the people. The environment should concern both indoor and outdoor public spaces in the BE and the final essential requisite is the heterogeneity of the attack typologies, which allows to investigate common and specific attack-related behaviours. As for previous works, videotapes are selected if related to reliable sources (e.g. Law Enforcement Agencies, Civil protection bodies, massmedia channels) and/or confirmed by them, as well as they freely available from the Internet [1]. The overall videotapes database by (Bernardini and Quagliarini 2021) moves into this direction and it is retrievable at https://drive.google.com/drive/folders/1H7SmChfkgQU1kEoMEZVQbAdK323gp1t7?usp=sharing.
According to the limitations in the adoption of the analysis of videotapes for behavioural investigations (compare to D1.2.5, Section 2), videotapes from personal devices of involved people (e.g.: smartphones) could be used, but being aware that the framing quality is frequently quite low and the image has no fixed views, thus limiting the application to quantitative analysis on motion.
According to previous works on the analysis of emergency evacuation conditions, each videotape should be divided into one or more "scenes" (Yang et al. 2011; Bernardini et al. 2016, 2019; Zhou et al. 2018). "Each scene has similar evacuation conditions and involves only an evacuation" process (Bernardini et al. 2016). Such "scenes" are preferably considered when all the following criteria are met:

1. The videos have to contain the most interesting phases of the event (pre-movement, evacuation and immediate post-evacuation phases); in each case, the scene has to show at least some people during the motion;

[1] e.g. from "YouTube" social media (https://www.youtube.com/ last access on 08/06/2020)

2. Videos displaying constant flows of people during the evacuation are preferred for the possibility to acquire physical measures, e.g.: instant velocity, data for fundamental diagrams;
3. The footage has to keep a minimum quality in order to distinguish individuals. In particular, they have to not show framing problems (e.g.: deleted frames; inadequate illuminance with the possibility to not continuously track human response; excessive camera movements);
4. Fixed cameras are preferred for the following quantitative analysis because they permit to focus the scene from an advantageous point of view (boundary conditions of the scenes are fixed), while evacuees' actions during the procedures are detected as long as possible.

According to the previous point 4, the videotapes are distinguished between those related to fixed cameras (e.g. surveillance cameras) or mobile cameras (including smartphones and by including the trigger proximity).

Furthermore, (Bernardini and Quagliarini 2021) proposes a classification of collected scenes based on the following *scenes characteristics*:

- *The type of attacks*, according to the threat types definition given in D1.3.2, Section 2 (e.g. *vehicle running into the target*, *bombing attacks* and so on);
- *BE in which the event occurs*, by subdividing them into indoor (i.e.: transport and buildings) and outdoor (i.e.: confined open spaces in the BE as urban streets, as well as unconfined ones as squares, parks and wide avenues) places (O'Neill et al. 2012; Lin et al. 2020);
- *presence of Safety/Security personnel*, to consider the visible influence of emergency authorities on the evacuation process, according to leader-follower interactions;
- *presence of "low" obstacles* (including fixed and movable ones) with which people can interact along the paths, e.g. that can be climbed/knocked over (e.g. barriers, railings, street furniture) while moving towards the targets;
- *Scenario modifications*, that is strictly related to the type of attack (e.g. bombing attacks). In this sense, the BE damages and modification could constitute impediment to evacuees' motion, by varying the boundary conditions to the evacuation process (Averill et al. 2005; Kobes et al. 2010; Li et al. 2017);
- *Trigger proximity*, since the individuals can perform different behaviors in relation to their position respect to the sources of the attack.

Finally, for each scene, the Level of Service (LOS) should be evaluated to trace the density of evacuees depending on the general limits classification (Transportation Research Board (TRB) 2000): A- up to 0.17pp/m^2, B- up to 0.27pp/m^2, C- up to 0.45pp/m^2, D- up to 0.72pp/m^2, E- up to 1.33pp/m^2, F over 1.33pp/m^2. LOS classification has been also combined (i.e. A+B, C+D, E+F) (Klüpfel and Meyer-König 2014) to define wider density ranges increasing the sample dimension. Qualitative evaluations on the overall LOS value can be performed in case of low level quality of the videotapes, as proposed by (Bernardini and Quagliarini 2021), i.e.: A+B: people moving in quasi free flowing conditions; C+D: movement in crowding conditions with limited physical contacts; E+F: movement with many (up to continuous) physical contacts. To this end, as well as for quantitative analysis purposes (see Section 2.3), opensource video analyzers (e.g. in (Bernardini and Quagliarini 2021), they used "Tracker" Version 5.1.5, https://physlets.org/tracker/ - last access: 02/07/2020) can be used to manually determine the density of people within a specific area defined by the user. As for activities described in D1.2.5, Section 3.3, the calibration of the spaces dimensions can be performed by using real-world dimension through plan data (e.g. for outdoor spaces, basing on Google Maps and Street View) and/or objects with known dimensions (e.g.: chairs, doors, cars), with a general approximation of 10cm.

In view of the above, it si worthy of notice that the reference work (Bernardini and Quagliarini 2021) provides one of the widest and most inclusive databases, although it involve only attacks from European Countries. 65% of the scenes refers to mobile cameras' videotapes. 70% of the scenes involves open spaces in the BE. Scenes are quasi-homogeneously characterized by armed assault (31%), vehicle running into the crowd (33%) and explosion (36%). For what concern the Level of Service classifications, the 40% of scenes refers to LOS A+B, while LOS C+D has a statistical occurrence of 19% and LOS E+F of 41%..

Safety/security personnel appears in 29% of scenes. Obstacles is registered in 50% of the scenes and in 59% of cases the environment was altered by the attack (especially in bombs explosion, e.g.: the presence of smokes). Finally, 70% of scenes are filmed in proximity to the attack source (in the following, "near"), thus strongly influencing the individual perception of imminent threats.

2.2. Qualitative analysis: methods

The qualitative analysis can be easily performed according to manual activities by trained researchers by detecting behaviors of individuals starting from those common to other kinds of evacuation (e.g. also compare to D1.2.5, Section 2.2). Then, the evacuees' behavioural patterns are investigated to highlight if additional responses in emergency could exist (Lambie et al. 2016; Bernardini et al. 2016). Such behaviors could be considered as statistically relevant (in the following, defined as *recurring behaviours*) if they are "present at least in the 30% of related cases", and they also can be classified between "common to other kinds of evacuation" (if present in other emergency conditions, e.g. earthquakes, floods, including those related to microscopic models, i.e. social force models) or "specific of this case" (if currently pointed out in reference to terrorism attack emergency conditions) (Bernardini et al. 2016; Bernardini and Quagliarini 2021).The organization of results is carried out by considering their occurrence in relation to:

- the *evacuation phases* (Bernardini et al. 2019): *pre-movement* (including the moments during the attack if it could be considered instantaneous); *evacuation phases* concerning the motion towards the evacuation target; *safe area reaching and immediate post-evacuation phase*. This representation allows to detect general outcomes on behavioral responses to the terrorist-related evacuation process;
- the *scenes characteristics* described above, so as to detect which are the most frequent registered behaviors for given same boundary scenarios conditions.

2.3. Quantitative analysis: methods

The quantitative analysis consists in the determination of physical measures connected to human motion during the evacuation, by using manual tracking techniques (compare to D1.2.5, Section 2.1 and Section 3), and to provide input data for fundamental diagrams of pedestrians' dynamic, which will compared with previous literature ones.

Different tracking systems for data collection of microscopic pedestrian traffic flow are provided from literature (Teknomo et al. 2001). The manual method can be chosen because of the videotape's characteristics such as the not uniform backgrounds to human motion or the images resolution (Yang et al. 2011; D'Orazio et al. 2014a; Bernardini and Quagliarini 2021). According to previous works (Chen et al. 2012; Bernardini et al. 2016; Shi et al. 2018), the analysis on scenes of the final dataset can be performed by using the open source image analysis software (compare to Section 2.2) on videotapes from fixed cameras or quasi-fixed images (e.g. mobile videos which not suffer from shaking over the analysis time and which framing view is focused on the same part of the BE) with adequate framing and quality, to have absolute references for body motion. Unidirectional motion scenarios by considering physical limits to pedestrians' motion can be preferred to this end. In particular, for indoor scenes, walls are identified as limits for pedestrians' motion. For outdoor scenarios, physical limits to the movement (e.g. building walls, street furniture and trees) are considered.

2.3.1. Individuals' quantities: evacuation speed

Once the videotapes have been prepared, a constant time step (ideally, 0.067s, that is 1 or 2 frames according to the videotapes framing features) should be chosen so as to trace the position of the evacuees, who are randomly selected between those that can be traced for a significant time in the scene (Bernardini and Quagliarini 2021). In particular, this reference work analysed individuals' instantaneous evacuation speed v_i [m/s] by considering LOS A conditions (ideally free-flowing motion conditions) in indoor/outdoor scenes, according to the main Section 2.2 classification methods. For each individual, v_i outliers were identified according to the Interquartile Range IQR method (fence: 1.5·IQR) (Rousseeuw and Hubert 2011).

The distribution and basics statistics of v_i were provided and the Anderson-Darling test (Anderson and Darling 1952) was performed to assess the type of main distribution of this sample data, i.e. Normal, Lognormal, and Weibull distributions, according to classical distribution of instantaneous speeds (Bernardini et al. 2016; Bosina and Weidmann 2017), by additionally providing histograms and cumulative frequency diagrams. In the following, comparisons to previous works outcomes about other kinds of evacuation and general purposes databases (Shi et al. 2009; Bernardini et al. 2016; Bosina and Weidmann 2017) as well as with D1.2.5, Section 4 results.

2.3.2. Fundamental diagrams-related analysis

Fundamental diagrams can use different methods for pedestrians' flows analysis. The so called "Method A" (Chen et al. 2012; Burghardt et al. 2013)traces the individuals' position in a quite simple manner, considering different period of time Δt referring to constant flows evaluation (the same group moving into the scene) (Zhang 2012). In "Method A", te cross-section width b [m] is assigned on a considered unidirectional path and the passing pedestrians are analyzed over Δt to evaluate the flow over time $<J>_{\Delta t}$ [pp/s] (depending on the number of individuals crossing the cross-section during Δt), the mean speed $<v>_{\Delta t}$ [m/s] (which depends on the average speed of the pedestrians within a small time interval Δt') and the pedestrian density $<d>_{\Delta t}$ [pp/m^2] (calculated as the ratio of $<J>_{\Delta t}$ and the multiplication between $<v>_{\Delta t}$ and b). In view of the above, Δt'=0.670s (corresponding to 10 frames so as to reduce the fluctuations of speeds due to center of mass positioning (Burghardt et al. 2013)), while b varies depending on the scenario. Then, indoor and outdoor "scenes" are separated in two subsamples, so as to consider the different fundamental diagrams (Bernardini and Quagliarini 2021). Both density-speed and density-flow pairs are discussed. In particular, for density-speed pairs, the Kladek formula described in Equation 2 is used to describe the pairs trends and provide a correlation for simulation models (Bruno and Venuti 2008) . The formula proposed by Kladek in 1966 was employed to describe the vehicular traffic case (Kerner 2004), and here is reconducted to the case of pedestrian trajectories of single file movement (Seyfried et al. 2010).

$$v_{F,hi}(\rho) = (v_{F,hf} - v_{min})\left\{1 - \exp\left[-k\left(\frac{1}{\rho} - \frac{1}{\rho_{max}}\right)\right]\right\} + v_{min} \qquad \text{If } 0 \le \rho \le \rho_{max} \qquad (2)$$

This empirical relation links the pedestrian speed at a given density $v_{F,hi}(\rho)$ [m/s] to four parameters: the preferred speed ($v_{F,hf}$), that can be considered as the ones for free flowing conditions (or rather, the one shown at the minimum experimental density); the maximum experimental density (ρ_{max}) and the related minimum experimental velocity (v_{min}), that is the one at the maximum density; and to a constant factor (k) that influences the curve shape. The Kladek formula is provided by considering density-speed pairs for: A) the whole sample; B) outdoor scenarios samples only; C) indoor scenarios sample only. The fittings accuracy is analyzed through the R^2 value and the Root Mean Square Error (RMSE) to evaluate the standard deviation of a typical observed value from the Kladek formula-related prediction.

Finally, (Bernardini and Quagliarini 2021) provided a comparison between this work experimental results and the main previous works outcomes about evacuations in terroristic attack and other cases such as (Hankin and Wright 1958) and (Mori and Tsukaguchi 1987), for the general purpose correlations (for both density-speed and density-flow pairs), and earthquake evacuation curves, such as those given in D1.2.5, Section 4.2 (in this case, only for density-speed pairs).

3. Evacuees' behaviors in terrorist attacks emergencies basing on existing databases: qualitative analysis results

Besides from the analysis of the 9/11 attack (Averill et al. 2005), previous works focused on the possibility of detection of alerts related to the attack (including risk-perception issues, also in view of the trigger proximity, that is the distance between the individuals and the source of the attack) and then to the activation of safety procedures and evacuation procedures, and the process of evacuation path selection (Li et al. 2017; Liu 2020). They also tried to include the analysis of staff members' actions (security) during the emergency (Liu 2020). Main results highlight that, after a pre-movement phase, people start running towards a safe area. Group effects common to other evacuation kinds are noticed and can influence the path selection as well as the speed of the overall group and its delay timing, thus evidencing pro-social issues in "panic" conditions (compare to Section 1.1). The influence of lack of information in the first evacuation stages is finally remarked as main driver for the possibility to adopt not appropriate choices in the evacuation process and to delay the evacuation procedure starting (Bruyelle et al. 2014).

In view of this general background, this section firstly discusses, for each of the evacuation stages introduced in Section 1.1, the *noticed behaviors [IDs codes referring to Figure 1]* (as in (Bernardini and Quagliarini 2021))according to the order of the evacuation stages in which they are performed..

3.1.1. Pre-movement phase

Since effects on the BE depend on the type of attack performed by terrorist, the event could be perceived by the crowd in different ways depending on the possibility to have or not widespread/evident scenario modifications and specific perceived cues, as for other emergency events in the BE (Lovreglio et al. 2016; Zhu et al. 2020). As a consequence, although common trends in pre-movement behaviours adoptions exist, differences between the type of attack are noticed (Bernardini and Quagliarini 2021).

In general terms, *"pro-social" behaviours [A]* can be generally performed in order to evaluate the effective emergency scenario, as for other kind of emergencies, thus leading the evacuees to also evaluate the possibility to start the evacuation process (Bernardini and Quagliarini 2021). Nevertheless, this behaviour generally shows a low statistical significance (under the 30% threshold), although an higher incidence seems to be correlated to specific scenarios conditions in which interactions among the evacuees could be increased, especially for: LOS E and F scenarios (due to improved communication exchange and group behaviours) (Bernardini and Quagliarini 2021) and when no safety/security personnel is present (Bañgate et al. 2017; Haghani and Sarvi 2018); proximity to the trigger (e.g. {Ma8, T10}), thanks to the possibility to effectively look for direct information on the event (Li et al. 2017; Liu 2020).

Meanwhile, the perception of the event through sensible cues generally provokes the activation of r*esponse to sensible events [B]* behaviours (Li et al. 2017; Liu 2020) especially when surrounding conditions allow the users to have a more free view of the scene, such as for people placed near the event trigger (e.g. {Br4,T2}), in indoor conditions and for lower pedestrians' densities. Concerning the type of attack, vehicles running into the crowd show frequency values under the 30% threshold essentially because of the surrounding conditions in which the attack happens (outdoors with lower pedestrians' densities) and on the duration of the attack itself (the trigger is an element moving into the scene rather than a localized one). Nevertheless, the related position between the trigger and the users is significant: When the trigger can be clearly seen by evacuees, the reaction time and the proper decision are improved (Bernardini and Quagliarini 2021).

Furthermore, different reactions can also be reconducted to the action performed by other people, because of indirect "pro-social" behaviours including "imitative behaviour" and herding in pre-movement responses (Haghani and Sarvi 2018). The event consequences in terms of injured people and deaths have demonstrated as such collective response in absence of clear information about the threat could be more dangerous than direct ones, confirming previous works on "phantom" panic and waves in the crowd (Helbing et al. 2002; Johansson et al. 2008; Helbing and Johansson 2010).

The *response to sensible event [B]* can also include the adoption of pre-movement safety behaviours (e.g. drop-hold on strategies) by means of additional *"pro-social" behaviours* (Bañgate et al. 2017; Haghani and Sarvi 2018). This phenomenon is underlined in case of attacks provoking sensible cues (e.g. armed assault with fire guns) or immediate modifications to the surrounding BE, (e.g. due to smokes or debris), and in reference to individuals who are placed near to the event trigger and can directly perceive it/its consequences. Nevertheless, the statistical significance of such behaviours appears to be marginal in respect to the general *response* behaviours and this results could be also affected by the sample dimension (Bernardini and Quagliarini 2021), as well as by different risk perception and risk awareness levels of the involved users (Lovreglio et al. 2016).

The *curiosity effects [C]* can be considered as an effective recurring behaviours (Bernardini and Quagliarini 2021), thus confirming previous works insights in other kinds of emergency evacuation (Kaigo 2012; Bernardini et al. 2017a, 2019). Main drivers to this behavioural response seem to be identified in the distance from the event trigger which can allow people to remain in safer conditions for a longer time, thus ignoring the evacuation procedure while shooting the scene. Nevertheless, people involved with the evacuation process can also use their mobile devices to shoot the disaster, as confirmed by mobile devices videotapes taken near the trigger and into the moving crowd, especially in outdoor conditions (Bernardini and Quagliarini 2021). It is worthy of notice that armed assault scenarios seem to have the lower significance of such behaviour , while explosion-related scenes the higher significance (up to over 70%), maybe because of the different rapidity in the evolution of the scene after the trigger appears (immediate in case of the explosion, while longer for armed assault).

3.1.2. Evacuation phase

As shown by its highest statistical significance, regardless of the specific conditions of the shrouding scenario, the *attraction towards safe areas [D]* and the related evacuation path choice affect the human behaviours in the evacuation phase (Bernardini and Quagliarini 2021), thus confirming the results of other previous common studies (Helbing et al. 2002; Haghani and Sarvi 2016; Liu 2018; Bernardini et al. 2019). It is worthy of notice that indoor scenarios and the scenes with no safety/security personnel refer to the higher probability of this behaviour activations, while the higher significance for people far from the event trigger could be also a consequence of the possibility to perform evacuation issues due to the proximity with the attack source (compare to pre-movement related behaviours described in Section 3.1.1).

People *running far from the event trigger [D.1]* can be mainly aimed at leaving the initial position in a short time and without a precise awareness about "where to go" and they could select the first available direction, including dead end paths (Bernardini and Quagliarini 2021). When the individuals are placed near the trigger source, the activation of the behaviours seems to be more evident. , This phenomenon can be seen in mono-directional spaces, such as corridors (including those of means of transportation, passageways and narrow streets), , in association with *running far from the event trigger* behaviour, as well as in spaces where people are confined (e.g. squares). The presence of such kind of behaviours in relation to lower density in pedestrians' crowd could be view as a result of the lower influence of *"pro-social" behaviours* in the evacuation process, which can underline the collective motion effects rather than the individuals' choices (Bernardini and Quagliarini 2021). Anyway, such results underline the BE layout affects the evacuation path selection as a paramount element in respect to the necessity to perform response actions under pressure conditions and with a limited familiarity with the surrounding spaces, also according to previous works (Koo et al. 2014; Li et al. 2017; Haghani and Sarvi 2018; Zhu et al. 2020). In this sense, the first available path/evacuation target perceived as safe seems to be one of the first evacuees' choice. This behaviour could also people to adopt risky behaviours, e.g. getting out of windows to be repaired from the terrorist attack such as in the Bataclan event (Bernardini and Quagliarini 2021).

As stated before, *"pro-social" behaviours [E]* highly affect the whole motion towards the evacuation target, as for other kind of evacuation (Bernardini and Quagliarini 2021). In particular, it can be noticed that *attraction for group ties [E.2]* and the possibility of *supporting more vulnerable individuals [E.2]* while moving is more relevant for lower LOS values, thanks to the possibility to better identify groups sharing motion purposes in the scene. Furthermore, it could be also noticed that: 1) the absence of safety/security personnel seems to increase both the effects because of the need in self-organization of groups during the motion process (Johansson et al. 2008); 2) attraction for group ties seems to be more relevant for people placed far from the event trigger, since here people can have minor pressure in actions performing (Koo et al. 2014; Haghani and Sarvi 2018). On the contrary, the *formation of evacuation groups in view of herding behaviors [E.3]* (and, marginally, the presence of *stop-and-go waves [E.4]*) is more relevant in presence of modifications to the BE induced by the attack source, and, mainly in higher density conditions, as expected (Johansson et al. 2008). Such kind of attractive phenomena underlines how *counterflow in evacuation motion [K]* have a significant impact (Bernardini and Quagliarini 2021), indeed.

Apart from attractive phenomena in motion, the individuals' trajectory seem to be limitedly affected by *repulsive mechanisms to avoid physical contact [F]*. It is worthy of notice that such modifications to the individual's motion towards the target can be significantly affected by the necessity to avoid people who *avoid performing evacuation procedures [J]*, thus additionally leading to possible pressures and collision between the users (Helbing and Johansson 2010). The avoidance to performing evacuation procedures could be amplified by the activation of social behaviours and curiosity-related effects, thus confirming outcomes of other kinds of evacuation (Bernardini et al. 2017a). As expected, it seems to be more relevant for people placed far from the event trigger, in outdoor cases (thus increasing the possible distances between the event source) and for LOS A conditions (due to the lower influence of crowd movement on the individuals) (Bernardini and Quagliarini 2021). Finally, the behaviour is limitedly affected the absence of safety/security personnel visible in the scene (lacking information about the emergency conditions and instruction to be followed), because of the general issues concerning guidance behaviours (see below in *[I]* discussion).

his trajectory to avoid people who remain in the same position and does not participate to the evacuation process {T5}.

Such repulsion phenomena seem to be limitedly activated in relation to walls, railings and chairs (in indoor), as well as fences, trees, street furniture and other movable elements (e.g. metal barriers), as also remarked in other kinds of evacuation (e.g. earthquakes, with the possibility to allow physical contacts or looking for them to get support (Bernardini et al. 2019)). In some case, people move from performing *not keeping a ‘‘safety distance” from ‘‘low obstacles” [G]* behaviours to *climbing over low obstacles/knock over mobile obstacles [G.1]* while moving, so as to minimize variations in the evacuation direction (e.g. {M8,T2, T5}). Such climbing and pushing behaviours are also outlined by previous works between the individuals placed in crowded/confined spaces (Helbing et al. 2002; Johansson et al. 2008; Schadschneider et al. 2009; Cornes et al. 2017), especially in LOS E+F conditions. In these cases, the pressure of the crowd in “stampede” conditions (can easily knock over mobile barriers and also fixed railings (Bernardini and Quagliarini 2021).As a result, low and movable obstacles (e.g. barriers) can become hazardous items for the evacuation motion (i.e. stepping in crowding conditions by potentially falling down and being stepped on by other pedestrians).

Moreover, individuals can decide to climbing low obstacles such as platforms to be safe from the stampede scene. Such behavior seems to be more relevant when people are placed near to the event trigger, by confirming the general trends in reaction due to proximity issues (Bernardini and Quagliarini 2021). Although knocking over of barriers seems to be essentially due to pressure phenomena inside the crowd, results additionally underline how *“Selfish” and competitive behaviours [H]* observed in previous studies (Drury and Cocking 2007; Haghani and Sarvi 2018) seems to be generally relevant in the analysed sample, also in correlation to the presence of low obstacles and for people placed near to the event trigger (thus relating the pushing phenomena with the overall crowd excitement)

The *guide effect for presence of rescuers [I]* (Averill et al. 2005; Fang et al. 2016) (Averill et al. 2005; Drury and Cocking 2007; Ji and Gao 2007; Li et al. 2015; Bernardini et al. 2019) seem to be limitedly not underlined in the investigated sample (under the recurring behaviour threshold for the whole sample), and mainly related to indoor environment and for people near to the event trigger (Bernardini and Quagliarini 2021). The reasons could be related to the crowd excitement in the immediate emergency response, as well as to the necessity by first responders (i.e. police officers) to respond to counterterrorism actions, while the sample dimension could influence the overall result. Anyway, examples of rescuers’ support to the exposed people regard (Bernardini and Quagliarini 2021) : a) in the evacuation process, direct physical guidance and assistance and support by instruction via Emergency Public Address Announcement and Alert Sound Systems; b) support to injured people in the immediate aftermath by also cooperating with evacuees.

3.1.3. Safe area reaching

In view of the attraction towards safe areas [D], once people arrive in outdoor scenarios, trends in *Safe area definition [L]* seem to be mainly related to specific BE and attack conditions, while the overall statistical significance seems to not reach the 30% threshold (as a consequence of the higher presence of behaviour *[J]*). Although results could be influenced by the sample dimension, results show how people tend to gather as far as possible from the event trigger/of the attack-damaged BE, confirming the fear against the event underlined by evacuation behaviours.

In some cases, the evacuation can due to the *influence of not immediate danger feelings or helplessness conditions [M]*, as for other kind of emergencies (Bernardini et al. 2019). For instance, positions considered as safe can be a raised platform in case of crowd stampede. This phenomenon seems to be relevant in case of higher pedestrians' densities, mainly as a consequence of group behaviours. The evacuation process ends in the first available safe area (compare to *[L]*) (Bernardini and Quagliarini 2021).

Environment layout and type of attack can influence the definition of the safe area as well as the evacuation end, especially in reference to fixed triggers (such as explosions) and movable ones (e.g. a vehicle running to the crowd, with a wider area of possible damages), especially in crowdy spaces (NaCTSO - National Counter Terrorism Security Office 2017), as well as in the view of possible wayfinding strategies (also compare with behaviour *[D]*). In case of an explosion, individuals can tend to interpose the most space as possible between them and the bombing site, especially in outdoor conditions. On the contrary, obstacles, walls, and barriers can protect people from weapon attacks or reduce the possible damage level, e.g. in case of vehicle running into the crowd. For this reason, exposed individuals can decide to escape towards (a) wider open spaces in the urban layout, placed far from the event trigger, or (b) behind obstacles or (c) inside shops (such as in "invacuation" procedures) (Bernardini and Quagliarini 2021).

In safe areas, people can gather by performing additional *"pro-social" behaviours [N]* (Averill et al. 2005), including those related to support to injured people, and then waiting for the rescuers' arrival, as for other kind of emergencies (Rao et al. 2011; Bernardini et al. 2019).

Individuals still try to perform *"Pro-social" behaviours in post-evacuation [N]* (Averill et al. 2005). Such "pro-social" behaviours are also activated in collaboration to safety/security personnel (compare to behaviour *[I]*) . *Attachment to things effect [O]* in the immediate aftermath could lead people placed in a close position in respect to the initial one to collect personal belongings in the event site (Riad and Norris 1996; Rao et al. 2011).

3.1.4. General outlines of the results and their statistical significance

Figure 1 offer the overview of noticed behaviours (including statistical significance) for the whole sample and just referring to the specific conditions in terms of main BE characterization elements, according to ther reference work results (Bernardini and Quagliarini 2021). In general terms, as graphically shown by Figure 1, the analysis on the whole sample generally underlines how a limited number of behaviours (generally, behaviours identified by IDs: C, D, E, G, H, J, K, L) seems to reach the significance threshold of 30%. This result could be affected by the sample dimension, as stressed by previous works (Bernardini et al. 2019) and in D1.2.5, Section 4 activities.

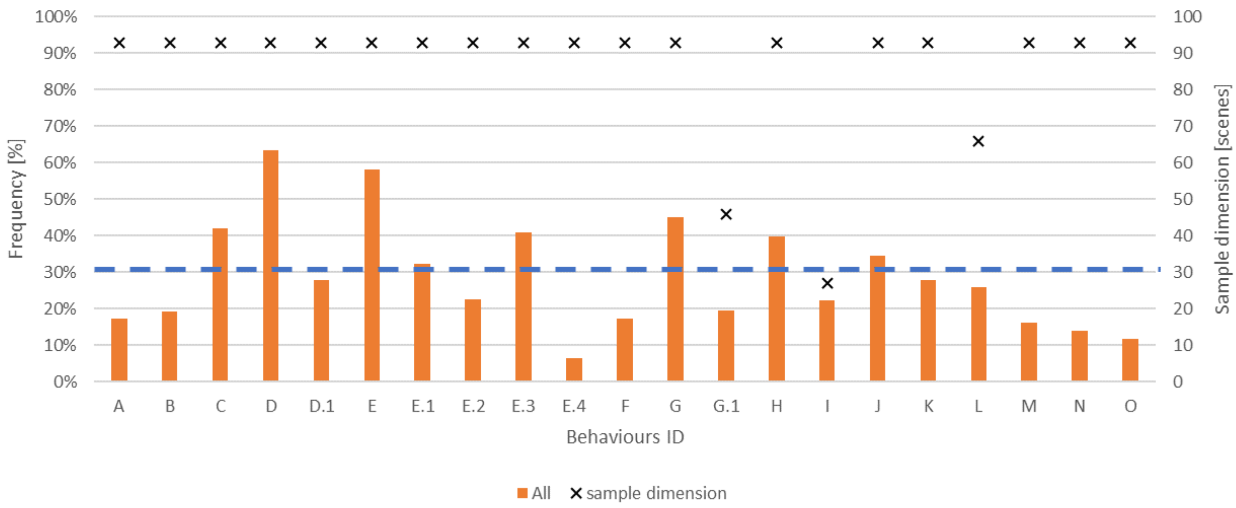

Figure 1. Activation frequency diagram of noticed behaviors as provided by (Bernardini and Quagliarini 2021). The sample dimension is also outlined (compare to left y-axis). The 30% threshold for behaviours is marked by the blue dashed line.

4. Evacuees' motion quantities

The aim of the quantitative analysis is to trace correlation among the physical quantities such as density, flow and velocity through the use of fundamental diagrams able to describe how pedestrians move within the emergency scenario. In this sense, results from (Bernardini and Quagliarini 2021) are discussed.

4.1. Individuals' evacuation speeds

According to (Bernardini and Quagliarini 2021), Figure 2 traces the histograms (density) and cumulative probability curves of v_i for the LOS A conditions, which data refers only to outdoor conditions, in respect to the Normal, Log-normal and Weibull distributions. v_i ranges from 0.17m/s to 8.4m/s (at 99th percentile, with a maximum value of 10.26m/s which seems to not be an outlier), with a median value of 3.16m/s and a mean (arithmetic mean) of 3.32m/s.

The Anderson-Darling test at 99% rejects the Normal and Log-Normal distributions, while the Weibull distribution (mean: 3.31m/s, variance: 3.76m/s; parameters estimate: A (scale)=3.72, std error: 0.08; B (shape)=1.77, std error: 0.06; A-B estimated covariance of parameters estimates always lower than 0.007) is not rejected. As remarked by (Bernardini and Quagliarini 2021), the average instantaneous evacuation speed in terrorist act evacuation seems to be:

- higher than general purpose evacuation speeds (mainly , fire evacuation) in indoor conditions (about + 120% in respect to about 1.4m/s, which falls in common exit speed ranges (Shi et al. 2009) also for walking conditions in non-evacuation motion (Bosina and Weidmann 2017), and is commonly used also in evacuation simulators (Lakoba et al. 2005). Differences due to indoor/outdoor spaces could exist from this point of view;
- similar to earthquake evacuation-related speeds in outdoors from previous works (about +13% in respect to average speeds of 2.95m/s given by (Bernardini et al. 2016)) and to D1.2.5, Section 4 (about +26% in respect to average speeds of 2.63m/s).

Furthermore, the overall limits for v_i have maximum values over common thresholds (e.g. about 6 to 7m/s for earthquake evacuation (Bernardini et al. 2016)). The adoption of a Weibull distribution underlines how the right tail in speed data could be connected to subtitles in evacuation behaviors (Shiwakoti et al. 2008). In this sense, future studies should investigate larger sample by evidencing differences over time of the evacuation speeds, so as to trace fatigue-related behaviors in maintaining high evacuation speeds.

Moreover, Figure 2 traces how the average speed values represent the different investigated conditions according to Table 2 and Table 3 summary, based on (Bernardini and Quagliarini 2021). Differences among the types of attacks seem to exist, by suggesting how the lowest speeds can be retrieved in case of explosion, also in case of lower density of pedestrians (, while spray attack registers the highest speeds, maybe because of the high excitement level of the evacuees also due to the trigger proximity.

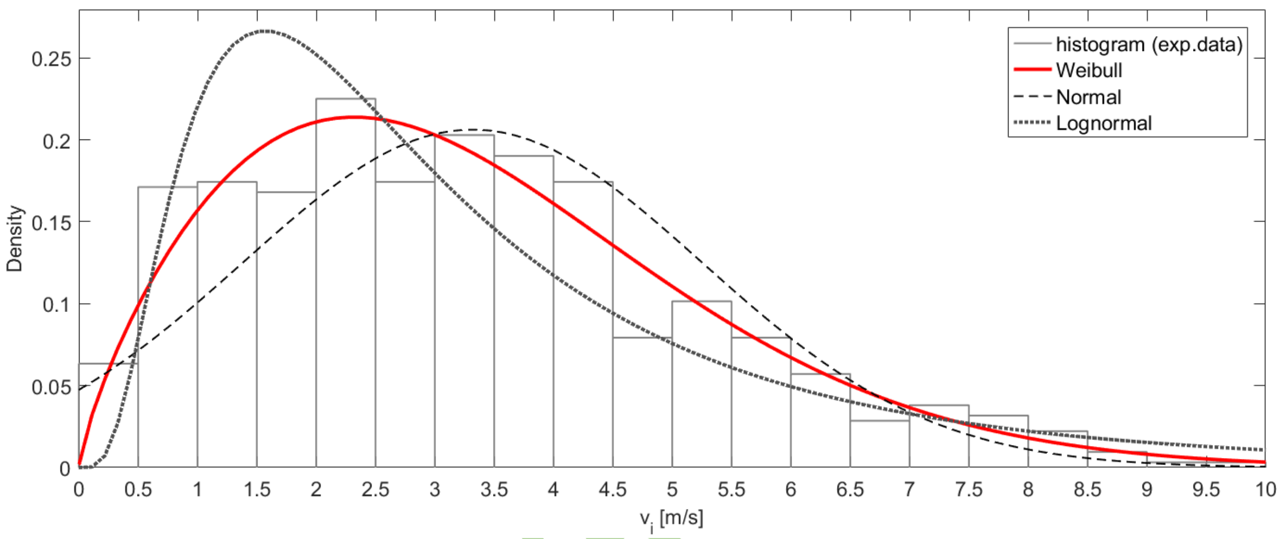

Figure 2. Evacuation speed distribution through Weibull, normal and lognormal distributions based on experimental data, in terms of density (and related experimental data representation through histogram). Data from (Bernardini and Quagliarini 2021)

Table 2. Summary of basic statistics for quantitative analysis on instantaneous evacuation speed v_i [m/s] for the whole sample and LOS A conditions. Data from (Bernardini and Quagliarini 2021).

Statistics vi data [m/s]	**all the sample**
Minimum (IQR-based)	0.17
Q1	1.85
Q2 (median)	3.16
Arithmetic mean	3.32
St. dev	1.93
Q3	4.44
99th percentile	8.40
Maximum (IQR-based)	10.26
Sample dimension	625

Table 3. Summary of sample dimension and average speed (aggregate sample) for quantitative analysis on average evacuation speeds calculated starting from v_i, depending on main scenario characterization elements. Data from (Bernardini and Quagliarini 2021).

Classification	Sample dimension [pp]	Average speed [m/s]
LOS		
A	21	3.64
B	18	2.51
D	6	2.73
E	6	2.29
F	8	1.35
Type of attack		
Vehicle	19	3.23
Fire guns	4	2.53
Spray	12	3.37
Explosion	24	2.12
Type of scenario		
Outdoor scenarios	38	3.07
Indoor scenarios	21	2.20

4.2. Fundamental diagrams

Concerning density-speed data, values from (Bernardini and Quagliarini 2021) are generally higher than the literature ones, especially by considering low-density cases. Such evidence can be explained by the influence of the high grade of threatening of the selected scenarios, which can increase the individuals' excitement in quasi free-motion conditions, as for the attraction towards evacuation behaviours discussed in Section 3.1.2. From a general point of view, similar results have been shown by other studies on disaster evacuation, e.g. in earthquakes (Bernardini et al. 2016) and could be related to both the sample dimension and the differences in pedestrians' excitement in non-controlled evacuation conditions. In this sense, main differences among data could be referred to different factors related to ethnicities and cultural background of involved agents, different environmental conditions, and finally to the specific moment in which data are collected (e.g. emergency or ordinary conditions) (Shiwakoti et al. 2008), thus underling the importance of collecting data on terrorist acts to define related emergency behavioural rules.

Figure 3 shows the overall sample distribution concerning such density-speed pairs, by tracing the Kladek-based regression (see Equation 3), while separated outdoor (see Equation 4) and indoor (see Equation 5) samples regression are also provided according to (Bernardini and Quagliarini 2021). In this sense, Annex A and Annex B respectively resumes the input pairs and the analysis of experimental-based errors given by the Kladek formula-based regression model in Equation 3.

Results mainly underline that the proposed Kladek formula-based regression models effectively suggest a vertical translation in respect to previous models (Mori and Tsukaguchi 1987; Bosina and Weidmann 2017). Hence, $v_{F,hi}(\rho_{max}) = v_{min} > 0m/s$, thus confirming results from previous works on experimental data about other kinds of emergencies (i.e. earthquakes (Bernardini et al. 2016), including those of D1.2.5, Section 4) and modelling approaches (e.g. the Q-model by (Lämmel et al. 2008)). Anyway, no maximum conditions of density leading towards null speed are noticed in the experimental sample, although the existence field for density values is lower than the common ones (general limits for pedestrians' movement blockage at about 5.0 to 5.5pp/m2 (Hankin and Wright 1958; Bosina and Weidmann 2017)). This result is due to the sample dimension of the considered study (Bernardini and Quagliarini 2021). *Figure 4* graphically summarizes the differences between this study regression model and references curves for: earthquake, as in (Bernardini et al. 2016) and in D1.2.5 Section 4; general purpose (Bosina and Weidmann 2017).

In view of the above, although data clearly shows that the increasing pedestrians' density implies a significant reduction in motion speeds, the indoor density values are more dispersed than the outdoor ones (thus affecting the final regression model estimate) as well as the density-induced reduction of speed is less evident (-30% for indoor sample and -88% for outdoor sample in respect to the measured speed at the minimum experimental density) (Bernardini and Quagliarini 2021). Moreover, the existence field for Equation 3 (both indoor and outdoor conditions) and Equation 4 (indoor conditions only) refers to $0 \le \rho \le 2.67\, {}^{pp}/_{m^2}$, while for Equation 5 (outdoor conditions only), it refers to $0 \le \rho \le 2.15\, {}^{pp}/_{m^2}$.

The *k* values at 95% of confidence, for Equation 3, are equal to 0.09 and 0.19 (which can move towards a speed-reduction trend shaping similar to those of outdoor sample conditions) (Bernardini and Quagliarini 2021). R^2 values The Kladek-based regression is characterized by R^2=0.57 and RMSE=0.43, while outdoor and indoor-related models show similar R^2 (about 0.44) and RMSE are respectively equal to 0.54 and 0.16. Although the prediction error seems to be lower in indoor-related conditions (compare the RMSE), such results can be affected by the sample dimension, as well as by the scattered input values, especially for outdoor sample conditions (i.e. the majority of data refers to density values over 0.5pp/m²).

$$v_{F,hi}(\rho) = (2.50\, {}^{m}/_{s} - 0.72\, {}^{m}/_{s})\left\{1 - \exp\left[-0.14\left(\frac{1}{\rho} - \frac{1}{2.67\, {}^{pp}/_{m^2}}\right)\right]\right\} + 0.72\, {}^{m}/_{s} \quad (3)$$

$$v_{F,hi}(\rho) = (2.50\, {}^{m}/_{s} - 0.31\, {}^{m}/_{s})\left\{1 - \exp\left[-0.19\left(\frac{1}{\rho} - \frac{1}{2.15\, {}^{pp}/_{m^2}}\right)\right]\right\} + 0.31\, {}^{m}/_{s} \quad (4)$$

$$v_{F,hi}(\rho) = (1.04\, {}^{m}/_{s} - 0.72\, {}^{m}/_{s})\left\{1 - \exp\left[-0.14\left(\frac{1}{\rho} - \frac{1}{2.67\, {}^{pp}/_{m^2}}\right)\right]\right\} + 0.72\, {}^{m}/_{s} \quad (5)$$

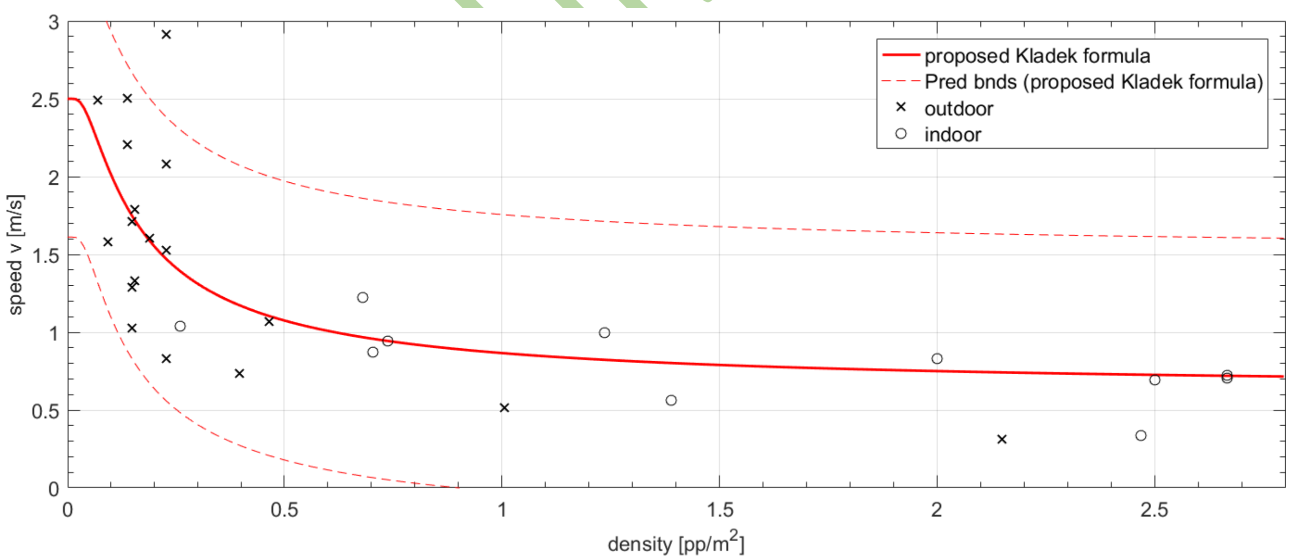

Figure 3. Kladek formula over the investigate sample (fitting on the overall sample), by including prediction boundaries at 95% of confidence (dashed red curves). From (Bernardini and Quagliarini 2021).

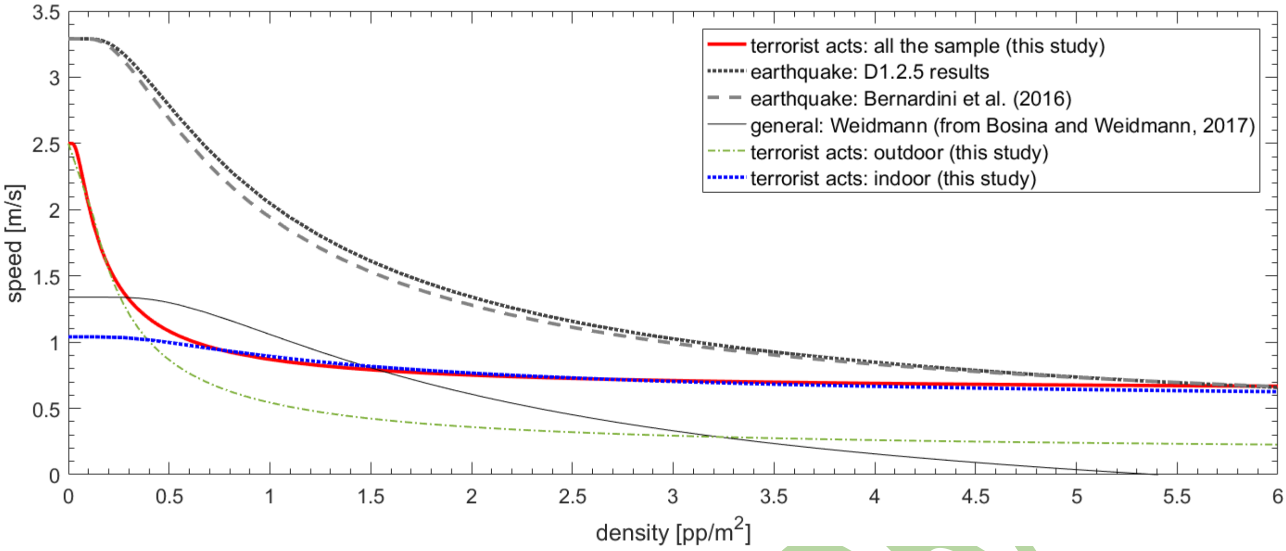

Figure 4. Comparison between Kladek formula proposed in different works (and D1.2.5) for different emergencies and the key findings of this work (for the whole sample and for outdoor sample).

5. Conclusions and remarks

Understanding main behavioural responses against a sudden onset disaster-related emergency is a basic element to better understand which risk-reduction strategies should be applied in the Built Environment (BE) to improve the exposed individuals' safety in case of quick arising danger conditions for the hosted community. Despite the large number of studies about emergency behaviours, terrorist attacks are not yet widely investigated from this point of view. This work is aimed at filling this lack by summarizing results from other research group works (Bernardini and Quagliarini 2021), which relies on data from videotapes of real events, taking advantages of the potentially unbiased sources for behavioural analysis.

Starting from literature outcomes analysis, a complete and unique database on qualitative and quantitative aspects in emergency behaviours is here provided by including statistical insights. Although the database is not still exhaustive due to its dimension, the database would be valuable for preliminary activities related to development, evaluation and validation of behavioural emergency evacuation simulators for terrorist attacks.

According to previously methodologies for behavioural analysis (compare to D1.2.5 Section 2 and Section 3), collected data are organized in relation to the evacuation phases as well as to the main drivers (i.e. the BE, the other individuals, the attack sources) and then compared to previous works results, thus underlining which behaviours are common to other kind of evacuations. While some common behaviours are still underlined (i.e. attraction towards safe areas, group interactions), results show how some behaviours can reach a statistical significance level by considering specific surrounding conditions in terms of BE and type of attack. Such outcomes remarks how the activation of emergency response is effectively affected by the context in which the occupants are placed, thus underlining the possibility to represent them by using agent-based models. Then, quantitative aspects of motion are performed by focusing on evacuation speeds and density-affected phenomena to define, for the first time, fundamental diagrams of pedestrians' dynamics in earthquake terrorist acts emergency conditions. In general terms, average speed values are higher than the ones of the majority of evacuation kinds, while similarities with earthquake evacuation process are retrieved (compare also to D1.2.5, Section 4). Hence, these results confirm that the evacuation simulator to assess terrorist acts effects through the crowd should take into account values different from those commonly applied to fire and general purposes simulations. In this sense, the definition of fundamental diagrams could be easily and directly applied to test simplified design procedures of BE configuration.

This work sample offers a significant overview on the terrorist acts emergencies, but future activities would enlarge the sample dimension of the previous reference works, by mainly focusing on the inclusion of more types of terrorist attacks typologies, also in the view of the main differences among their effects on the crowd. Furthermore, the effective influences of geographical, social and cultural background (including preparedness and risk-awareness issues) on emergency behaviours should be assessed, as for other kind of emergencies, by combining data from videotapes to other kind of investigation methodologies (e.g. surveys, virtual reality tests). Anyway, the database outcomes would be soon used for simulators definitions and validations, also in view of activities in the BE S^{2}ECURe project, i.e.: typological assessment and simulation activities in WP3 and WP4, taking advantages case-studies for complete simulators verifications; virtual/augmented reality-based activities for training in WP6, to additionally compare if differences between real world behaviours and such laboratory experiments could exist, and then train people and first responders on how to correctly face such disaster conditions.

This work really represents the first needed step to improve evacuation simulation software for terrorist acts analysis, in view of the assessment of emergency management procedures (including evacuation plans) and of the other risk-mitigation strategies to be deployed in the BE. Simulations results will allow to underline the possible interactions between the effects of the attack (and the attackers, too), the BE and its modifications, the crowd and the first responders in view of such an emergency. Pedestrians' flows and paths characterization will can be combined to analysis on the evacuation time and on the causalities' number, so as to underline the effects of such interactions and the possibility to reduce risk by structural and management-related actions, towards the assessment of community resilience aspects in such scenarios. Finally, results will also can suggest observations for risk-awareness campaign and training of the population, so as to improve the community resilience from a bottom-up perspective.

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Annex A

Annex A - Table 1. Evaluated values for each analysed attack (i.e.: density, threshold length, number of agents, considered time intervals, flow, normalized flow and mean velocity.

Environment	Attack	Density [p/m²]	Threshold [m]	No. person	Δt [s]	Flow [p/s]	Normalized flow [p/s/m]	Mean velocity [m/s]
Outdoor	Stockholm	0.157	11.2	22	7	3.143	0.281	1.791
		0.072	11.2	8	4	2.000	0.179	2.494
		0.094	11.2	5	3	1.667	0.149	1.583
		1.006	4.5	14	6	2.333	0.519	0.515
	Turin	0.139	13.1	8	2	4.000	0.305	2.203
		0.191	13.1	20	5	4.000	0.305	1.602
		2.150	3.9	29	11	2.636	0.676	0.314
		0.396	12.0	21	6	3.500	0.292	0.737
	Nice	0.229	10.5	5	1	5.000	0.476	2.080
		0.229	10.5	8	4	2.000	0.190	0.832
		0.229	10.5	7	1	7.000	0.666	2.912
		0.229	10.5	11	3	3.667	0.349	1.525
		0.149	13.1	3	1	3.333	0.255	1.714
		0.149	13.1	8	4	2.000	0.153	1.029
		0.149	13.1	5	2	2.500	0.192	1.286
	Paris	0.465	4.30	20	5	2.143	0.498	1.071
	Bruxelles Airport	0.156	9.60	20	10	2.000	0.208	1.333
		2.469	1.80	6	4	1.500	0.833	2.500
Indoor	Manchester	2.469	1.80	6	4	1.500	0.833	0.338
		1.389	1.80	7	5	1.400	0.778	0.560
		1.235	1.40	5	3	1.667	1.235	1.000
		0.681	1.80	6	4	1.500	0.833	1.224
	Bruxelles Metro	0.260	4.80	13	10	1.300	0.271	1.040
		0.704	6.0	9	2.5	3.68	0.614	0.872
		0.737	6.0	8	2	4.18	0.696	0.945
	Madrid	2.000	2.0	20	6	3.333	1.667	0.833
		2.500	2.0	38	11	3.455	1.727	0.691
		2.667	2.0	45	12	3.750	1.875	0.703
		2.667	2.0	27	7	3.857	1.929	0.723

Annex B

Annex B - Table 1. Evaluated data related to Kladek formula application.

Density [p/m²]	Kladek velocity [m/s]	Experimental Velocity [m/s]	Percentage difference [%]	Mean velocity [m/s]	Mean velocity percentage difference [%]
0.072	2.868	2.494	14.99	2.494	14.99
0.094	2.792	1.583	76.35	1.583	76.35
0.139	2.578	2.203	17.00	2.203	17.00
0.140	2.571	2.500	2.82	2.500	2.82
0.149	2.523	1.714	47.20		
0.149	2.523	1.029	145.34	1.343	87.92
0.149	2.523	1.286	96.27		
0.156	2.485	1.333	86.41	1.333	86.41
0.157	2.483	1.791	38.63	1.791	38.63
0.191	2.309	1.602	44.14	1.602	44.14
0.229	2.128	2.080	2.35		
0.229	2.128	0.832	155.87	1.837	15.86
0.229	2.128	2.912	26.90		
0.229	2.128	1.525	39.56		

0.260	1.993	1.040	91.65	1.040	91.65
0.396	1.549	0.737	110.28	0.737	110.28
0.465	1.387	1.071	29.42	1.071	29.42
0.681	1.041	1.224	14.95	1.224	14.95
1.006	0.754	0.515	46.40	0.515	46.40
1.235	0.632	1.000	36.79	1.000	36.79
1.389	0.570	0.560	1.74	0.560	1.74
2.000	0.410	0.833	50.81	0.833	50.81
2.150	0.384	0.314	22.02	0.314	22.02
2.469	0.338	0.338	0.04	0.338	0.04
2.500	0.334	0.691	51.69	0.691	51.69
2.667	0.314	0.703	55.29	0.713	55.92
2.667	0.314	0.723	56.53		