MONTE CARLO AGENT-BASED HOSPITAL EVACUATION SIMULATIONS.
THE PRINCIPLES OF PERFORMANCE-BASED INCLUSIVE DESIGN

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ABSTRACT
In emergency, while the majority of the occupants recognise the risk and start the evacuation process autonomously, the people who need assistance do not necessarily act in that way. Trained and skilled staff are required to rescue those needing help, avoiding the risk of discriminatory response and failure. A few modelling approaches are available to assess the egress of people who need assistance to evacuate, since both physical and cognitive aspects should be considered. In this study, an agent-based approach has been adopted with a focus on the behavioural rules assigned to the agents depending on their characteristics and goals. A unified framework has been proposed to establish a standard codification of the occupant profiles: based on their mobility and way-finding abilities, occupants are classified into a basic set of five categories. For each occupant category, the mobility device and the staff assistance eventually required are specified. Apart from occupant characteristics, it is necessary to define the service discipline. consisting of three components: the staff skills and consistency, the scheduling policy, and the mobility device eventually required to relocate the assisted occupant. The movement of people as groups is also considered. The inclusive approach proposed in this study has been implemented using the Pathfinder software and applied to the analysis of the assisted evacuation scenario of a hospital ward. In order to demonstrate the ability to simulate complex evacuation plans, the horizontal relocation of the In-patients to refuge areas located on the same floor is combined with the vertical transfer of one In-patient using a firefighters lift. The stochastics variables representing the occupant characteristics and the service discipline have been described by probability distributions, including both autonomous and assisted profiles. The Monte Carlo methods provide the means to address the parameter uncertainty in probabilistic risk analysis. Based on the Central Limit Theorem (CLT), the number of trials required for a specified accuracy in the evacuation time modelling is obtained using a predictor-corrector scheme applied to the worked case. The principles of performance-based inclusive design are thus established, with proper consideration of the occupants who need assistance, the assisting staff role and the service discipline. This approach can be considered a generalization of the conventional Required Safe Escape Time (RSET) evolving into the Required Safe and inclusive Escape Time (R*i*SET).
Keywords: *People with disabilities; Mobility impairment; Horizontal assisted evacuation; Monte Carlo simulation, Human behaviour; Evacuation modelling; Inclusive design; Convergence criteria*

1. Introduction

Life safety in buildings and its technical requirements respond to a wider range of concerns than just fire hazards, requiring an ordered and controlled movement of people in emergency conditions and planning in advance where people can be safely located [1-3]. Protection of occupants is achieved by the combination of prevention, protection, egress, and other measures [4-5]. When deciding the strategy of evacuation, all forms of escape routes should be considered, including the use of refuges for people with disabilities or lifts specifically designed to provide protection from the immediate danger from fire [6]. The number of and skills and training of the staff assisting the occupants in the evacuation scenario should also be considered, especially if someone cannot autonomously reach a place of safety [7-10]. Life safety goals and objectives shall be met with due consideration for the occupancy functional requirements. Typical emergency procedures aim to avoid the need for simultaneous evacuation, especially in buildings which accommodate occupants who are mostly incapable of self-preservation, due to their age or physical/cognitive disability, or are confined in locked rooms or wards in places of "lawful custody" (e.g., prisons, police stations and specialized psychiatric hospitals). When required by the evacuation plan or prescribed by national or local codes [1,4-5], refuge areas are provided to limit the number of people impacted and reduce the distress that might be caused to vulnerable occupants, serving as temporary locations that provide a place of relative safety to a predefined number of occupants. A refuge area might be another building connected by a bridge, a compartment of a subdivided story, a protected lobby or stairway or a corridor complying with the accessibility requirements foreseen in the national building regulations and standards [11-12]. Fire safety codes provide prescriptive guidance concerning the means of escape and the evacuation strategy. Provision of adequate escape routes and refuge areas equipped with means of communication to a manned location, staff reaction and preparedness, notification and communications systems to alert the occupants are key elements to be considered, especially in occupancies such as health and day care facilities, where there are likely to be many persons to be assisted in an emergency situation [13-14].

A full review of evacuation models is given for instance by Kuligowski et al. [15-16], Vermuyten et al. [17], Ronchi et al. [19-20] and unveils that most published studies are focused on the autonomous evacuation in building or transportation. Few studies deal with the numerical simulations or experiments of assisted evacuation scenarios, mainly concerning hospitals: Tsuchiya et al. [21-23], De-Ching et al. [24], Golmohammadi and Shimshak [25], Ze-min et al. [26], Alonso et al. [27-28], Hunt et al. [29-32], Yokouchi et al. [33], Ursetta et al. [34], Rahouti et al. [7].

This paper presents three main contributions. First it reports a standard codification of the occupants, including those who need assistance, suitable to be implemented in agent-based models (ABM) for evacuation developed over recent years. Based on their mobility and way-finding abilities, occupants are classified into a basic set of five categories, considering the general disabilities categories proposed by the NFPA DARAC guide [35]. Each category may originate a variety of occupant profiles which are applied to specific groups of building occupants. *Assisted evacuation* is modelled as a queueing process, with a prescribed *service discipline*, consisting of three components: the *staff skills and consistency*, the *scheduling policy*, and the *mobility devices* eventually required to relocate the assisted occupant. The relocation tasks are executed according to the *scheduling policy,* by one or more *assisting operators* having the necessary *skills,* using *a mobility device* if needed.

The principles introduced in Section 2 are applied in Section 3 to the simulation of the horizontal assisted evacuation of a hospital ward combined with the vertical transfer of one in-patient using a firefighter elevator, showing the potential to assess complex evacuation strategies. As most input parameters are represented by stochastic variables, a single scenario may produce a distribution of possible outcomes (e.g., the evacuation time). It is therefore critical to enable the designer to make informed decisions on when to terminate the simulations. Researchers have proposed various methods for judging when enough simulations have been run [36-39]. The second contribution is a *prediction-correction* convergence scheme suitable to be implemented in existing agent-based models, to obtain an estimate of the total number of repeated runs required to obtain a specified accuracy in evaluating the evacuation time (and the relocation times) distribution. Besides the mean and the standard deviation, the method also includes the proportion of the simulations concluded with all occupants relocated or exited, being a measure of system performance. The application of the convergence scheme to the worked case provides an example of its use and strength.

The third contribution concerns the generalization of the conventional Required Safe Escape Time (RSET) to include the occupants who need assistance and their service discipline, introducing the Required Safe and *i*nclusive Escape Time (R*i*SET) concept. While the RSET calculation is traditionally based on deterministic methods, R*i*SET requires a probabilistic risk assessment. The 99th percentile evacuation time prediction is proposed as a key parameter to calculate one characteristic R*i*SET value to be used in performance-based design.

This approach will well serve the fire protection engineering professional by providing guidance on the quantitative human behaviour analysis needed in the performance-based design, relating theory to practice.

2. Method

2.1 Occupant profiles and evacuation capabilities

The Protective Action Decision Model (PADM) provides a theoretical framework that describes the information flow and decision-making that influences protective actions taken by occupants in response to an emergency scenario [40]. In case of a fire, the perceptions of the physical cues (e.g., the sight of smoke or the heat exposure or the asphyxiant or toxic gases inhalation) as well as information from the social environment (e.g., from people inside the building or emergency messages or warnings) must be processed by each occupant to assess the threat and eventually start the evacuation [41].

The selection of the occupant profiles to be used in the evacuation modelling is a critical task and should provide an accurate reflection of the expected population of building users. Occupant characteristics include factors such as gender, age, physical/cognitive/sensory capabilities, familiarity with the building, participation in emergency training, social and cultural roles, presence of others and commitment to activities [42]. Four basic people characteristics have been identified in the Life Safety Code © [1] that can affect a fire safety system's ability to meet life safety objectives: *sensibility* to physical cues, *reactivity* (ability to interpret cues correctly and take appropriate action), *mobility* and *susceptibility to products of combustion.* Individual physical and mental capabilities must be combined with social and contextual factors like alertness, the condition of being alone or with others, familiarity with the building and training. Separated group members are likely to attempt to re-establish their unity before moving towards the exit and their speed of movement is often dictated by that of the slowest member while attempting to stay together in proximity [43-44].

Evacuation capability is defined in [1] as the ability of occupants, residents, and staff *as a group* either to evacuate a building or to relocate from the point of occupancy to a point of safety. It is a function of both the ability of the occupants to evacuate and the assistance provided by the staff, if any. It is determined using the procedure acceptable to the Authority Having Jurisdiction (AHJ) with the application of the standard NFPA 101A [45] or evaluated "experimentally" by a program of drills performed by persons approved by or acceptable to the AHJ.

If an occupant cannot reach the public way or an area of refuge with minimal intervention from staff members, such as a verbal or a visual (e.g., sign language) communication, classification as incapable of self-preservation [46-47] should be considered and active staff/emergency response assistance during the evacuation or relocation activities should be included in the emergency plan. Examples of direct intervention by staff members include carrying an occupant, pushing an occupant outside in a wheelchair or bed or stretcher, and guiding an occupant by direct hand-holding or continued bodily contact, as detailed in the NFPA DARAC guide [35] that outlines the four elements of evacuation information that occupants need: notification, way finding, use of the way, and assistance.

Occupant disabilities can be classified according to the general categories - mobility impairments, visual impairments, hearing impairments, speech impairments, cognitive impairments - reported in Table 1, derived from NFPA DARAC guide [35]. It is not uncommon for people to have multiple disabilities, combining for instance mobility impairment with cognitive or sensory deficit. A similar approach has been proposed in Italy by an expert panel (Serra [48]), inspired by the International Classification of Functioning, disability and health (ICF) [49], developed by the World Health Organization (WHO).

Table 1: Disabilities classification derived from NFPA DARAC Guide (2016) [35].

General category		**Examples of mobility devices required**
Mobility	*Ambulatory mobility*	Canes, crutches, walkers
	Wheelchair users	Power-driven or manually operated wheelchair
	Respiratory	Depending on the case
Blind or Low vision		Canes, service animals.
Deaf or Hard of hearing		
Speech disabilities		
Cognitive disabilities		Depending on the case
Temporary disabilities		Depending on the case

The disabilities classification reported in Table 1 is reformulated as shown in Table 2 for application in evacuation agent-based computer models. Mobility is combined with way-finding ability to obtain a basic set of five *occupant categories* establishing a standard codification of evacuation capabilities. For each occupant category, the mobility device and the staff assistance eventually required are specified [95]. The *Autonomous* category applies to occupants having full way finding capability and ability to independently walk on even and uneven surfaces and negotiate stairs. Depending on the skills and training received, this category might assist other occupant categories. The *Autonomous with mobility devices* category refers to occupants having full way finding capability but impaired in their movements by the necessity to use a mobility device. *Type a*) applies to those occupants that can move/walk independently through an accessible route, at least for relocation on the same floor. *Type b*) is reserved to those occupants that may also be able without supervision to negotiate stairs with the use of a one-handed device. The *Autonomous requiring assistance in way finding or notification* category refers to occupants requiring assistance. *Type a)* applies to those occupants able to walk but requiring assistance in way finding or walking, due to their age or sensory impairments or unhealthy conditions. *Type b)* is reserved to those occupants requiring assistance only needs to be notified of the emergency. The last two categories – *Not autonomous* – apply to the *assisted* evacuation of patients transferrable only using a *mobility device* or a *bed/incubator*. In both cases, *Type a)* applies to patients transferrable only an accessible route (for relocation on the same floor). *Type b)* is reserved to patients transferrable on stairs. In the case of a patient transferred using a *mobility device*, it refers to the use of an emergency travel device or a firefighters lift (e.g., complying with the standard EN 81-72 [50], clause 5.2.3) accessible for a wheelchair or a stretcher (e.g., types 3 to 5 according to the standard EN 81-70 [50]). In the case of a *bed*, the patient is transferrable on stairs only by means of a firefighter lift, with adequate accessibility (e.g., type 5 according to the standard EN 81-70 [51]).

Anthropometric data may be also considered to introduce further distinction related to gender or age or body shape, being mainly reserved to characterize the *autonomous* profiles.

The term *meta-communication* has been introduced by Ponziani et al. [~~51~~52] to identify the interaction (e.g., the set of actions and verbal and visual communication) that is necessary to establish with the assisted occupant in order to include people with disabilities in the evacuation process. As the *meta-communication* may require specific abilities and training to the care giver, it is necessary to distinguish in the simulation (and in the evacuation instructions) the roles of staff employees and emergency responders, depending on their skills and the characteristics of the assisted people. When a *link* is established, a *group movement scheme* shall be considered in the evacuation modelling, with the care giver acting as a leader with the responsibility to select the travel path.

The degree of impairment should be considered together with building environmental factors; for instance the locomotive ability of an individual can be enough to move effectively along corridors or limited inclination ramps (e.g., *Type a)* sub-category) but inadequate to descend a stairway (e.g., *Type b)* sub-category). Hence the evacuation capability assessment shall be properly conducted taking into account both the specific occupancy and the population investigated.

Table 2: Occupant evacuation capabilities basic categories

Mobility and way finding capabilities category	**Mobility device**	**Assistance**	**Examples**
1. *Autonomous* Full way finding capability and ability to independently walk on even and uneven surfaces and negotiate stairs. Depending on the skills and training, may assist other categories.			• *Staff/Emergency response teams* • *Walking patients (priority classification level 4* [1]*)*
2. *Autonomous with mobility devices* Full way finding capability. *Type a*): move/walk independently through an accessible route (at least for relocation on the same floor). *Type b*): with the use of a one-handed device may also be able to negotiate stairs without supervision.	Cane, crutch, walker, wheelchair		• *Temporary or permanent disabilities*
3. *Autonomous requiring assistance in way finding or notification* *Type a):* able to walk on even and uneven surfaces and negotiate stairs only with the assistance of another person in way finding or walking. *Type b):* able to walk on even and uneven surfaces and negotiate stairs but requiring assistance only to be notified of the emergency.		*1 or 2 operators for each autonomous walking occupant*	• *Blind or Low vision persons* • *Cognitive disabilities* • *Children* • *Deaf or Hard of hearing* (only to be notified of the emergency) • *Walking patients (priority classification level 3* [1]*)*
4. *Non autonomous - mobility device required* *Type a):* transferrable only on a wheelchair, a stretcher or a rescue sheet through an accessible route (for relocation on the same floor). *Type b):* transferrable on stairs with emergency travel devices or by means of a firefighters lift (e.g., complying with EN 81-72 [50], clause 5.2.3) accessible for a wheelchair or stretcher (e.g., types 3 to 5 according to EN 81-70 [51]).	Wheelchair, stretcher, rescue sheet, emergency stair travel device	*1 to 4 operators for each assisted person*	• *Non autonomous patients (priority classification level 2* [1]*)*
5. *Not autonomous – Transferrable only with beds or incubators* Type a): transferrable only with a bed or incubator through an accessible route (for relocation on the same floor). *Type b)*: transferrable on stairs only by means of a firefighters lift (e.g., complying with EN 81-72 [50], clause 5.2.3) with adequate accessibility (e.g., type 5 according to EN 81-70 [51]).	Bed, incubator	*1 to 2 operators for each assisted person*	• *Critical patients (priority classification level 1* [1]*)*

[1] Patients priority classification according to the National Association for Home & Care Hospice [53].

2.2 Basic occupant profiles

Each of the five general categories reported in Table 2 may originate several occupant profiles, depending on the occupancy considered. A basic set of *autonomous* profiles, including mobility impaired people, is given in Table 3, with the key parameters required to describe the *individual* horizontal evacuation capabilities in ABM simulations. For the sake of simplicity, no gender or age differentiation is here considered, even if it could be necessary at least for the Active staff and the Emergency responders, which are the profiles in charge of the assistance tasks. It might be possible to use the gender and/or age split when the specifics of the model scenario are known. A comprehensive literature review of *unassisted* movement speeds for *people with disabilities* is available in the SFPE Handbook of Fire Protection Engineering [16], in Appendix G of ISO/TR 16738 [54], and in Geoerg et al. [55].

Table 3: Basic evacuation capabilities for autonomous occupants, including mobility impairments

Autonomous occupant profile	**Unrestricted walking speed (m/s) (on level terrain, straight-line)**					**Social grouping/ Role**	**Remarks**
	Distribution law						
	Type	*μ*	*σ*	Min	Max		
Active staff *(in each fire compartment)*	Normal [1]	1.35	0.25	μ -2.8σ	μ +2.8σ	Individual or assistance team member	Familiar & Trained
Emergency response *(in the emergency control center)*	Assumed equal to Active staff					Individual or assistance team member	Familiar & Trained
Generic autonomous occupant	Normal [2]	1.20	0.20	μ -3.0σ	μ +3.0σ	Individual or groups, eventually linked to one assisted profile	Uncertain familiarity & Not Trained
Worker *(not in charge of evacuation assistance)*	Assumed equal to generic autonomous occupant					Individual or with co-workers	Familiar & Trained
Autonomous in-patient *(in hospital and care homes)*	Normal [3]	0.95	0.32	μ -2.2σ	μ +2.2σ	Individual or linked to autonomous occupants	Uncertain familiarity & Not Trained
Autonomous but mobility impaired [4]: *Crutches*	Normal [3]	0.94	0.30	μ -1.0σ	μ +1.4σ	Individual or linked to autonomous occupants	Uncertain familiarity & Not Trained
Autonomous but mobility impaired [4]: *Walking stick*	Normal [3]	0.81	0.38	μ -1.4σ	μ +2.0σ	Individual or linked to autonomous occupants	Uncertain familiarity & Not Trained
Autonomous but mobility impaired [4]: *Rollator or walking frames*	Normal [3]	0.57	0.29	μ -1.6σ	μ +1.6σ	Individual or linked to autonomous occupants	Uncertain familiarity & Not Trained
Autonomous but mobility impaired [4]: *Electric wheelchair*	Constant [3]	0.89				Individual or linked to autonomous occupants	Uncertain familiarity & Not Trained
Autonomous but mobility impaired [4]: *Manual wheelchair*	Normal [3]	0.69	0.35	μ -1.6σ	μ +1.9σ	Individual or linked to autonomous occupants	Uncertain familiarity & Not Trained

[1] Based on Alonso and Ronchi [28] averaged data for health care staff members. Data differentiated for gender are available in the IMO guidelines [56], which assumes a uniform distribution of velocities in the range 0.93-1.55 m/s for female and 0.93-1.55 m/s for male members of the crew.

[2] Based on Fruin [56] averaged data (all age classes and gender); similar values are reported in Boyce et al. [58] A constant speed of 1.19 m/s is proposed in the SFPE Engineering Guide to Human Behavior in Fire [42].

[3] Based on Boyce et al. data [58]. Other sources of data are available in literature (e.g., Miyazaki et al. [59]).

[4] A simplified approach is proposed by Alonso et al. [27-28] with a unique profile, assuming a uniform distribution of velocities in the range 0.84-1.40 m/s.

It is convenient to categorise the “rescuers”~~,~~ through the assignment to different “emergency” teams, the Active staff and the Emergency response personnel, to prescribe specific set of rules concerning the use of the means of escape (e.g., elevators) or specialised skills. Following Gwynne et al. [60-61], the Active staff profile is here used to identify those employees having a procedural role in case of emergency, rather than simply being responsible for evacuating as quickly as possible. It is assumed that the Active staff are *already assembled in the corresponding compartment* and are prepared for performing the assigned evacuation tasks [27-28, 60-61]. The Emergency response profile is reserved to occupancies protected by an emergency control center, which is usually provided in all buildings designed for phased evacuation and in large and complex buildings [13, 62]. The emergency responders are specialized operators who are trained in the building emergency management systems and procedures, supervising the protected activity from their control center. These operators are not firefighters of the local fire and rescue service. A basic set of *assisted* profiles, including *autonomous* occupants requiring support in way finding and those who need the aid of mobility devices, is given in Table 4. The assisted ambulant profile applies to occupants with cognitive or sensory impairments requiring support, even only for emergency notification, but no mobility aid. It is assumed that a constant number of assisting operators (but variable for each assisted profile) performs both the preparation phase, discussed in the following section 2.3, and the transportation phase, using the prescribed mobility device.

Table 4: Basic assisted occupant profiles and travel speed in ~~the~~ horizontal route

Assisted occupant profiles	**Assisted travel speed (m/s) (on level terrain, straight-line)**					**Number of assisting operators**
	Distribution law					
	Type	μ	σ	Min	Max	
Assisted ambulant [1]	Normal	0,71	0.34	μ -1.7σ	μ +1.8σ	*1 operator* [3]
Assisted transported on a wheelchair [2]	Normal	0,63	0,04	μ -3.0σ	μ +3.0σ	*1 operator* [3]
Assisted transported on a carry or evac chair [4]	Uniform			1,34	1,75	*1 operator* [3]
Assisted transported on a bed [2]	Normal	0,40	0,04	μ -3.0σ	μ +3.0σ	*2 operators*
Assisted transported with hand-held rescue sheet [4]	Uniform			0,52	1,23	*2 operators*
Assisted transported with a hand-held stretcher [4]	Uniform			0,91	1,23	*4 operators* [5]

[1] Based on Boyce et al. data [58].
[2] Based on Alonso et al. data [27-28] (minimum and maximum values assumed). Data for evacuation and carry chairs transportation are available in Hunt et al. [30-31].
[3] An additional operator may be needed to prepare the patient for transportation or assist along the travel path.
[4] Based on Hunt et al. [29-31] overall data, discarding gender differentiation.
[5] Could be reduced to two operators only to execute the task to prepare the patient for transportation.

Assisted evacuation is usually considered in health care evacuations and is modelled as a queueing process where several “clients” (the occupants who need assistance) request the service of one or more assisting operators having the necessary skills to help [7, 28, 63]. It is therefore necessary to define the *service discipline*, consisting of three components: the *number* and *skills of assisting operators,* the *scheduling policy,* and the *mobility devices* eventually required to relocate the assisted occupant. Various scheduling policies can be adopted but usually the following two suffice:

- *priority*: assisted occupants with the highest-ranking need are served first;
- *distance*: assisted occupants closest to a free assisting member, having the necessary skills, are served first.

In the first case it is necessary to establish an evacuation order list. In both cases, if more than one assisting operator is needed, the assisted occupant shall wait for the whole team to assemble.

2.3 Pre-travel activity times and preparation times

The pre-travel time or pre-travel activity time (PTAT) is defined in international standards and technical documents [42, 54, 64]as the interval between the time at which a warning of a fire is given and the time at which the first move is made by an occupant towards the exit. The PTAT consists of two components: *recognition time* and *response time*. The *recognition time* is the interval between the time at which an alarm warning of a fire is given and the first observable response to the warning. Depending on the fire scenario, occupants might be aware of various fire cues before or after a warning is given. The *response time* is the interval between the time at which the first observable response to the event occurs and the time at which the movement begins towards an exit or a safe location. The provision of reliable data on the pre-travel activity times expected in various situations and their incorporation into evacuation agent-based models is an important requirement for the assessment of evacuation time. Guidance on default values is given in Annex E of PD 7974-6 [64], which updates Annex E of ISO/TR 16738 [54]. The conventional definition of PTAT is applicable only to the autonomous occupant categories not requiring assistance in evacuation (self-evacuation, categories 1 and 2 in Table 1). For the emergency teams (Active staff and Emergency response profiles), a different PTAT definition is proposed in literature [65-66] as the time elapsed between the warning of fire being given (e.g., the alarm) and positive evacuation activities by staff. This differentiation is important as this time relates to their participation in the procedure rather than only their self-evacuation; it therefore directly relates to the time for staff to interpret the nature of the event and commence their response [67]. PTAT can be represented by a log-normal statistical distribution [27-28, 64]. For well-managed cases (denoted by M1 in PD 7479-6 [64] and ISO/TR 16738 [54]) such as the scenario investigated in Section 3, the minimum PTAT for *autonomous* occupants in engineering application is in the order of *30 s*. Active staff's PTAT mean and standard deviation values are taken from Alonso et al. [27-28], for health care occupancies. The maximum value is reported in Gwynne et al. [60-61]. If the occupancy is protected by an emergency control center permanently staffed by Emergence responders, shorter PTAT parameters are expected for this profile than those assigned to the Active staff, due to their roles and responsibility [42]. Emergency responders are assumed in this study to move within *60 s* upon receiving the alarm notification. All the other occupants having autonomous evacuation capabilities are specified to start their movement within *120 s* (ISO/TR 16738 [54] for awake and unfamiliar in medical care occupancy). The PTAT adopted in this study for *autonomous* occupant profiles are given in Table 5. Active staff have higher pre-evacuation statistical parameters than Other autonomous profiles, having uncertain familiarity and training. This could occur by several reasons. First, different PTAT definitions applies to emergency teams and to the other autonomous profiles, as this time relates to their participation in the procedure rather than only their self-evacuation. Secondly, the table is based on available literature data obtained by different sources and, when specific data are lacking, expert judgement is used. This issue outlines the importance of calibrating model input to establish whether the results of the simulations correctly predict the relevant evacuation scenario [42].

Table 5: PTAT for autonomous occupant profiles adopted in the simulation of assisted evacuation

Autonomous occupant Profile	**Pre-travel activity time (s)**					**Remarks**
	Distribution law					
	Type	μ	σ	Min	Max	
Active Staff	Log-normal [1]	71[1]	60 [1]	30 [3]	246 [2]	Familiar & Trained
Emergency response	Log-normal [3]	43	6.44	30 [3]	60	Familiar & Trained
Other autonomous profiles *(Autonomous occupant, including those mobility impaired)*	Log-normal [4]	62.7	19.11	30 [4]	120 [4]	Uncertain familiarity and training & Not grouped with an assisted occupant

[1] Based on Alonso et al. data [27-28] for health care staff.

[2] Values derived from Gwynne et al. [60-61].

[3] Based on ISO/TR 16738 [54]; data range for awake & familiar profiles in level M1 occupancies.

[4] Based on ISO/TR 16738 [54]; data range for awake & unfamiliar profiles in level M1 occupancies.

For occupants who need assistance to evacuate, it is necessary to define the *preparation time*, representing not only the time required to prepare the occupant with mobility impairment for relocation [27-28] but also the time (and *skills*) needed to establish a *communication link* with a person having cognitive or sensory impairments. The timings given in Table 6 are only for guidance in medical care occupancies and depend on the assisted people involved, the staff training, the equipment available and the degree of maintenance provided.

Table 6: Preparation times for assisted occupant profiles

Assisted occupant profile	**Preparation time (s)**				
	Distribution law				
	Type	μ	σ	Min	Max
Assisted ambulant [1]	Normal	60	20	μ -1.5σ	μ +1.5σ
Assisted transported on a wheelchair [1]	Normal	110	36	μ -0.3σ [3]	μ +0.3σ [3]
Assisted transported on a bed	Assumed equal to assisted on a wheelchair				
Assisted transported on a carry or evac chair [2]	Normal	41.5	7.9	μ -1.2σ	μ +1.3σ
Assisted transported with a hand-held rescue sheet [2]	Normal	65.2	14.1	μ -1.4σ	μ +1.5σ
Assisted transported with a hand-held stretcher [2]	Normal	77.7	19.2	μ -0.9σ	μ +2.2σ

[1] Based on Alonso et al. data [27-28].
[2] Based on Hunt et al. overall data [29-30] for carry chair for an assisting team of two health care operators.
[3] Based on Hunt et al. overall data [29-30] for an assisting team of two health care operators.

2.4 Movement Groups

The nature of the social relationship between the occupant and the surrounding population is among the factors that can influence evacuation performance. A group of occupants who share an affiliation link, such as a family or a visitor to an in-patient or a guided group, will have a strong tendency to stay together and move as a group [68-70], sharing their way-finding behaviour following *a leader* while travelling toward a common destination. Movement groups schemes are thus determined by the type of occupancy considered. In *inclusive* design, groups should also consider occupants who need assistance, due to their physical or cognitive impairments [7, 28].

Movement schemes during the evacuation are differentiated in two classes, depending on the characteristics of the occupants forming each group:

a) groups formed only by occupants having autonomous evacuation capabilities (category I and II in Table 2, profiles listed in Table 3);
b) groups including both assisted occupants (category III, IV and V in Table 2, and profiles listed in Table 4) and the autonomous occupants (different from the assisting staff).

2.5 Evacuation time probability distribution: number of iterations and accuracy of single loop Monte Carlo methods

As our evacuation model includes the use of probabilistic variables to simulate the variability of possible agent behaviours, a single scenario may produce a distribution of different occupant evacuation time curves. Monte Carlo (MC) simulations, which rely on repeated random sampling of a problem having multiple stochastic inputs in order to generate a distribution of possible results, represent a method of analysis particularly suited to deal with the system of interest.

According to PD 7974-7, a probabilistic risk assessment (PRA) should reflect the variability in the risk and take into account the uncertainty associated with the risk estimate. Sources of uncertainties in evacuation modelling are classified into three main groups [71]:

a) *parameters uncertainties (epistemic* or *aleatory)*, concerning specific estimates or values used in setting up the evacuation model, mainly related to the human factors: pre-evacuation times, walking speeds, preparation times, anthropometric data;
b) *model uncertainty,* related to the assumptions made in underlying scientific knowledge and theoretical models or empirical relationships on which is based the selected evacuation model;

c) *completeness uncertainty,* concerning issues that are excluded from the analysis but are known to exist, such as human behaviours deviating from rationality or not following the optimal strategy in wayfinding or propensity for fatigue.

As a first step, we assume that no epistemic uncertainty exists in the evacuation model; the probability distributions listed in Tables 3 to 6 represent the intrinsic randomness of the relevant parameters. The MC methods provide a mean to address the *parameters uncertainty* and can be considered as the most basic form of random sampling of a problem having multiple stochastic inputs to generate the probability distributions of possible outputs. Random realizations of all stochastic variables are initially generated and are used within the deterministic simulation model in order to return a single model realization. The process is repeated in order to evaluate the range and probability distribution of possible outcomes: this scheme is also known as the single loop (1D) MC solution. Alternative sampling schemes exist, such as Latin hypercube or orthogonal sampling, which samples more accurately from the entire range of input distribution functions, or more complex MC methods are available, such as the double-loop MC method [71] or the "boostrapping" technique [72]. As more sophisticated approaches are restricted to the research applications and are not implemented in any available evacuation software for fire safety engineering applications and considering the burden on computing resources required by performing hundreds or thousands of repetitions as requested by bootstrap statistical technique, a single loop Monte Carlo technique has been selected in this study. PRA based on MC trials should provide a clear statement regarding the relationship between the number of iterations executed, *n*, and the confidence limits, associated with a specified supplied confidence level(s), for the outputs of interest. The number of trials necessary is dependent on both the degree of accuracy and the sensitivity of the results of interest (mean, variance, proportion of population, etc.), especially if a tail of the distribution is investigated [71]. The procedure is here described with reference to the evacuation time, the key variable in fire safety engineering, but its application to relocation times or occupant exit times is straightforward.

It is anticipated that the convergence of the ET may not guarantee that the full range of evacuation dynamics has been adequately represented [38], as will be shown in Section 4.2 with reference to the worked case described in Section 3.

2.5.1 The number of Monte Carlo simulations required to obtain the desired precision

Before we obtain data there is uncertainty about the evacuation (and relocation) times distribution. The number of iterations *n* required to achieve a specific bound on the half-width of the Confidence Interval (CI) cannot easily be estimated *a priori*. Many inferential statistics are based on the properties of the *sampling distribution mean*, whose importance derives from its use in drawing conclusions about the *population mean,* thanks to the Central Limit Theorem (CLT), which states that as the sample size increases *the sample mean* will be *normally distributed* for most underlying distributions. *Assuming the model is correct*, one can obtain as small a statistical error as desired by conducting a sufficiently large number of trials.

Let ET represent the evacuation time population for a given scenario with *a priori* unknown distribution, having a mean of μ_{ET} and a variance σ_{ET}^2. The calculated simulations results { $et_1,\ldots,et_n$ } are assumed to be the result of a random sample $ET_1, \ldots, ET_n$ of size *n* drawn from the ET population. Let then consider the distribution of the sample mean, $\overline{ET}$, consisting of *all* estimations of the ET distribution's mean possible by averaging random samples of size *n* drawn from ET, that has a mean of $\mu_{\overline{ET}}$ and a variance $\sigma_{\overline{ET}}^2$. If *n* is sufficiently large, the CLT states that $\overline{ET}$ asymptotically approach the *normal distribution*, *no matter the ET population distribution*, so that:

$$\mu_{\overline{ET}} = \mu_{ET};\ \sigma_{\overline{ET}}^2 = \sigma_{ET}^2/n \tag{1}$$

and the 100*(1 – α) % two-tails classical confidence interval for the mean μ_{ET} of the ET distribution is given *approximately* by:

$$P(-z_{\alpha/2} < \frac{\mu_{\overline{ET}}-\mu_{ET}}{\sigma_{ET}/\sqrt{n}} < z_{\alpha/2}) \approx 1-\alpha \quad (2)$$

If *ET* has a *normal* distribution, *irrespective of the sample size n*, the sample mean $\mu_{\overline{ET}}$ is *normally* distributed with expected mean equal to μ_{ET} and standard deviation equal to $\sigma_{ET}/\sqrt{n}$ (a quantity often called the standard error of the mean estimator). The quantity $z_{\alpha/2}\frac{\sigma}{\sqrt{n}}$ is called Δ, the half-width of the Confidence Interval (CI) of the mean, associated with a two-tails α confidence level.

Using the sample average ($\overline{et} = \sum_{i=1}^{n} et_i/n$) and standard deviation ($s_{et} = \sqrt{\sum_{i=1}^{n}(et_i - \overline{et})^2/(n-1)}$) as unbiased estimators for the $\mu_{\overline{ET}}$ and σ_{ET}, the classical CI for μ_{ET} is obtained:

$$\overline{et} - z_{\alpha/2}\frac{s_{et}}{\sqrt{n}} < \mu_{ET} < (\overline{et} + z_{\alpha/2}\frac{s_{et}}{\sqrt{n}}) = et_{max} \quad (3a)$$

$$\Delta_{\mu_{ET}} = z_{\alpha/2}\frac{s_{et}}{\sqrt{n}} \quad (3b)$$

Formulas 3a) and 3b) should be strictly applied only when *n* is sufficiently large to justify their use but have the strong advantage to be valid *regardless of the shape of the population distribution.* The accuracy of the mean estimator ($\Delta_{\mu_{ET}}$) should increase as the number of trials, *n*, increases; *if the model is properly formulated*, this is statistically true with the potential error in the approximation being proportional to $1/\sqrt{n}$.

When the number of trials *n* is small, typically less than about 30 or 40 [73], the *t* distribution has to be used, having a similar shape but requiring an additional parameter, the degrees of freedom, ν, determined as the number of trials minus one. For a small sample, formula 3a) is replaced by:

$$\overline{et} - t_{\alpha/2,\nu=n-1}\frac{s_{et}}{\sqrt{n}} < \mu_{ET} < (\overline{et} + t_{\alpha/2,\nu=n-1}\frac{s_{et}}{\sqrt{n}}) = et_{max} \quad (3c)$$

Eq. 3c) is equal to Eq. 3) in Grandison work [38] (and in any study invoking the CLT for small samples).

Inferences concerning the CIs for the population variance σ_{ET}^2 or standard deviation σ_{ET} are more difficult to obtain when the population distribution is *not normal.* Skewness or heavy tails can have a drastic impact on the asymptotic coverage probability of the normal-based confidence intervals [74]. Bonett [75] proposed a confidence interval that performs well in small samples under moderate departures from normality. His interval performs only slightly worse than the exact normal-based confidence interval when sampling from a normal distribution. A larger sample size provides Bonett confidence intervals with greater protection against nonnormality. Supposing that the ET population distribution is *normal*, the 100*(1 – α) % two-tails classical CI for the variance σ_{ET}^2 is:

$$\frac{(n-1)}{\chi^2_{1-\alpha/2,\nu=n-1}} s_{et}^2 = \sigma^2_{ET_{min}} < \sigma_{ET}^2 < \frac{(n-1)}{\chi^2_{\alpha/2,\nu=n-1}} s_{et}^2 = \sigma^2_{ET_{max}} \quad (3d)$$

The confidence coefficients - $z_{\alpha/2}$ or $t_{(\alpha/2,\nu)}$ or $\chi^2_{\alpha/2,\nu=n-1}$ and $\chi^2_{1-\alpha/2,\nu=n-1}$ - are obtained from tables reporting their values as a function of confidence levels (α) and the degrees of freedom (ν) in case of *t* and χ^2distribution [73].

In evacuation modelling, the designer is generally interested in *the upper tail* of the evacuation time distribution [76], being a measure of the system performance (the RSET criteria, discussed in section 5). This key point is not discussed by Grandison [38] and is only touched with no specific detail or guidance in Lovreglio e al. [37]. Thus, this paper includes the estimation of the accuracy in evaluating *a specified proportion of the simulations concluded with all occupants correctly relocated or exited* (e.g., the probability *p* of successfully completing the evacuation at a specified time). The derivation of the CI for a population proportion, *p*, based upon a random sample of size *n*, can be found in any text on introductory statistics [73]. The Wilson score method is here adopted, being best suited for small values of *n* and when *p* is close to 0 or 1 (extreme values). The half-width of the

CI, $\Delta_{p_{ET}}$, for the proportion p_{ET} of ET population with confidence level approximately 100(1-α)%, is given in Eq. 4b), being centred on $\tilde{p}_{ET}$ given in Eq. 4a), involving the unknown a priori $\hat{p}$, the sample fraction of "successes", that is advantageously obtained *after* conducting a first set of MC trials.

$$\tilde{p}_{ET} = \frac{\hat{p} + z_{\alpha/2}^2/2n}{1 + z_{\alpha/2}^2/n} \tag{4a}$$

$$\Delta_{p_{ET}} = z_{\alpha/2}\frac{\sqrt{\hat{p}(1-\hat{p})/n + z_{\alpha/2}^2/(4n^2)}}{1 + z_{\alpha/2}^2/n} \tag{4b}$$

These equations do not state directly how many iterations should be performed or, more importantly, how accurate the resulting estimation is. These are important issues that the designer should address including a justification for the criteria adopted. An appealing strategy is to specify *a priori* the confidence level, α, and the half-interval width, Δ, and estimate the number of required iterations *n* to the desired degree of precision, from the application of formulas 3b) or 4b):

$$n_{\mu_{ET}} = \frac{z_{\alpha/2}^2\, s_{et}^2}{\Delta_{\mu_{ET\,design}}^2} \tag{5a}$$

$$n_{p_{ET}} \cong \frac{z_{\alpha/2}^2}{2\Delta_{p_{ET\,design}}}\left(\frac{\hat{p}(1-\hat{p})}{\Delta_{p_{ET\,design}}} - 2\Delta_{p_{ET\,design}} + \sqrt{\hat{p}(1-\hat{p})\left(\frac{\hat{p}(1-\hat{p})}{\Delta_{p_{ET\,design}}^2} - 4\right) + 1}\right) \tag{5b}$$

As $n_{\mu_{ET}}$ is proportional to the s_{et}^2, its convergence should be monitored during the MC realizations. The method proposed in [95] is focused on the accuracy achieved in the estimation of the key stochastic variable of interest in performance-based design, the evacuation time, rather than the vector representing the exit/relocation times of each individual occupant considered by other Authors [36-39]. Moreover, it gives an explicit formulation of the estimate of the required number of simulations to achieve a desired accuracy in the mean or in the proportion of the evacuation time distribution (Eqs. 5a) and 5b)).

2.5.1.1. A predictor-corrector convergence scheme for Monte Carlo evacuation modelling

One common way of terminating an egress MC simulation scheme is to continue running until the observed fluctuation (variation) of the estimated quantity of interest has "stabilized" [36-38, 71]. Although this methodology probably will meet its objectives, it does not allow the user to know in advance how long the simulation will run. Also, such an approach often requires a larger number of runs than are really necessary. The convergence scheme is similar to the one proposed by Lovreglio et al. [37] or by Grandison [38], that adapt to evacuation modelling a common procedure in conducting MC studies [77].

Suppose that one is prepared to run a minimum of n_{min} and a maximum of *N* Monte Carlo realizations. n_{min} should be greater than 40 to invoke the use of CLT to estimate the CI *regardless* of the nature of the population distribution concerned. The basic procedure is outlined with reference to the evacuation time, the key variable in fire safety design, but its generalization to relocation times or occupant exit times is straightforward.

1. Conduct first a *small number of egress simulations,* in order of $n_1 \cong 10$, to obtain rough estimates of the mean ($\overline{et}^{n_1}$) and of the standard deviation ($s_{et}^{n_1}$) of the evacuation time (ET). Calculate the first estimate of $n_{\mu_{ET}}^{n_1}$, using the *t* distribution critical values (being a small sample). This is the "prediction" step.
2. Perform an additional round of ≈ 30 simulations (to obtain a sample of about $n_2 \cong 40$ trials).
3. Recalculate the mean ($\overline{et}^{n_2}$) and standard deviation ($s_{et}^{n_2}$) of the ET sample and its descriptive statistics. Check if this ET sample is *normally distributed*, and if so, calculate the lower and upper bound of the ET population variance ($\sigma_{et_{min}}^{n_2}, \sigma_{et_{max}}^{n_2}$). Using the *z* statistics, update the achieved

accuracies ($\Delta^{n_2}_{\mu_{ET}}, \Delta^{n_2}_{p_{ET}}$) and the number of trials required to achieve the design accuracy on the mean (~~$n^{n_2}_{p_{ET}}$~~ $n^{n_2}_{\mu_{ET}}$). This is the (first) "correction" step, which should refine the estimation on the number of trials necessary to perform to achieve the required accuracy.

4. Check the convergence termination condition, on the accuracy on the mean of the ET sample: ($n_2 \geq \max\,(n^{n_2}_{\mu_{ET}}, n_{min}$).
5. If the termination condition is *not* verified *and* $n_2 < N$, perform an additional round of ≈ 30 runs (or the quantity needed to reach maximum design number N) and repeat step 3 and 4 until convergence is reached or the maximum number of simulations N is approached (meaning that the design accuracy is not achieved).

This scheme establishes, within the CLT general framework, the convergence of a set of repeated evacuation simulations, within predefined acceptance criteria, towards the mean of the ET population distribution which could be obtained by performing an infinite number of trials. It is recommended to monitor during the iterative process the convergence of the ET sample variance and test if normality distribution applies, and simultaneously to check the convergence of the other key parameters (i.e. RTs).

2.6. Introducing inclusivity in performance-based design: the RiSET criterion

Life safety is the key functional objective of performance-based fire safety design [4, 42, 64]. Life safety goals consider a time-based comparison between two key factors:

1) ASET – depending upon parameters related to the fire dynamics and tenability conditions for the occupants
2) RSET – depending on pre-travel and travel behaviours of the occupants

as a mean of demonstrating, conducting a quantitative analysis, that the design meets the performance criteria.

ASET is calculated by fire models, based on (a cluster of) design fire scenarios while RSET is determined using evacuation models. The calculations can be executed independently, using different simulation tools and then reconciling the data in order to determine the time before untenable conditions exist in occupied spaces, or performed in an integrated application where both the fire model and the evacuation model are executed simultaneously. A simplified scheme of the process related to escape is conventionally expressed using a timeline as shown in Figure 1. The underlying strategy is the *simultaneous evacuation* of *all autonomous* occupants (or a *group* of occupants immediately at risk in case of phased evacuation) on sounding of an alarm. This approach is not fully adequate to bring *inclusivity* inside the fire safety design. In emergency, while the majority of the occupants recognise the risk and self-evacuate finding autonomously the way-out, the people who need assistance do not necessarily act in that way.

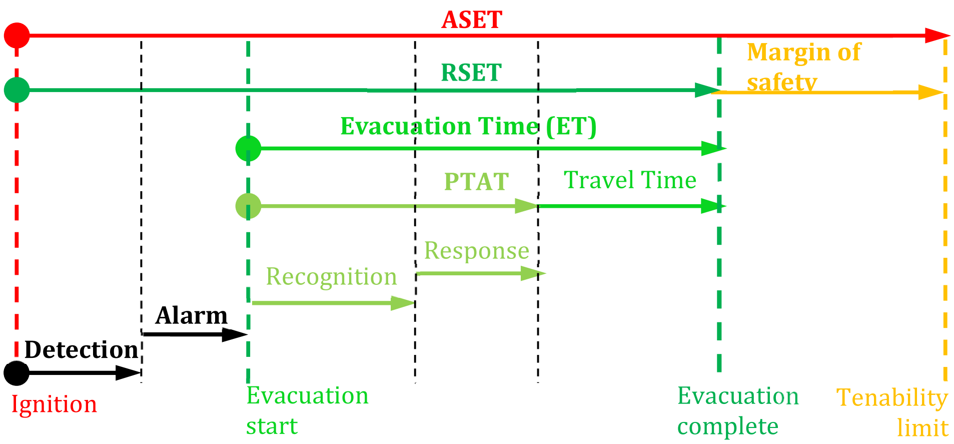


Figure 1: Conventional approach: RSET vs ASET [64]

Trained and skilled staff operators are required to contact those needing help that could unwillingly otherwise remain inside, avoiding the risk of discriminatory response and failure due to the lack of additional planning or special accommodation for people with disabilities, reduced staff or staff not having the necessary training, unavailability of mobility devices [35].

Based on the principles outlined in this Section, this study proposes a generalization of the conventional Required Safe Escape Time (RSET) introducing the Required Safe and *inclusive* Escape Time (R*i*SET) criterion to include the *occupants who need assistance* and their *service discipline.* This approach allows to establish a standard codification of occupant evacuation capabilities, *being autonomous or needing assistance.* The basis of performance-based inclusive design is illustrated in Figure 2. While the RSET calculation is traditionally based on deterministic methods, R*i*SET requires a probabilistic risk analysis. It is assumed that each autonomous occupants, classified in categories 1 and 2, starts its evacuation on sounding of an alarm and begin to move when its PTAT is expired. The destination is a place of safety for the occupants classified in categories 1 and 2 type a), which are able to walk on even and uneven surfaces and negotiate stairs, while it is a safe refuge for the occupants classified in category 2 type b).
Assisted evacuation is required for occupants classified in the categories 3 to 5. Assisting operators are differentiated in Active staff and the Emergency response to prescribe specific set of rules concerning the use of the means of escape (e.g., elevators) or specialised skills. The Active staff identifies those employees having a procedural role in case of emergency, *already assembled in the corresponding compartment* and are prepared for performing the assigned evacuation tasks. The Emergency response are specialized operators who are trained in the building emergency management systems and procedures, supervising the protected activity from the emergency control center. Active staff and Emergency response start their PTAT activities on sounding of the alarm. Again, both the PTAT and unrestricted walking speed, are stochastic variables specific for each category. Each assisting operator starts to move when its PTAT is expired; the unrestricted walking speed is used only along the path toward an assisted or after having completed all the assigned service tasks. The *service discipline* defines how the occupants who need assistance are served by one or more assisting operators, consisting of three components: the assisting staff *skills and consistency,* the *scheduling policy,* and the *mobility device* eventually required to relocate the assisted occupant. The dashed circle in Figure 2 exemplifies the *scheduling policy* adopted in serving the occupants who need assistance, requiring a number of missions to move them from their initial positions to the design destinations. A mission could be:

- assisting a person who is blind or low vision or with reduced mobility while walking along the means of egress;
- notifying the emergency to a person who is deaf or hard of hearing and who rely on lip reading for information;
- establishing a link with a person with cognitive disabilities (requires an operator with special training or skills, known to the assisted person) and then providing guidance to and/or through the means of egress;
- preparing a person with reduced mobility to be relocated using a mobility device.

Thus, *movement group schemes* are a necessary component of any inclusive design model, with the constraint that a group can include only one assisted occupant with one or more autonomous occupants sharing a social or assisting *link*.

The *Autonomous occupants requiring assistance only to be notified the emergency,* category 3 type b), move autonomously to a place of safety only after they are contacted by an assisting operator.

The *Autonomous occupants requiring assistance in way finding,* category 3) type a), applies to those occupants able to walk but requiring assistance in way finding or walking, due to their age or sensory impairments or unhealthy conditions.

Categories 4 to 5 – *Not autonomous* – apply to the *assisted* evacuation of patients transferrable only using a *mobility device* or a *bed/incubator*. In both cases, *Type a)* applies to patients transferrable only an accessible route (for relocation on the same floor). *Type b)* is reserved to patients transferrable on stairs. In the case of category 4, occupant transferred using a *mobility device*, it refers to the use of an emergency travel device or a firefighter lift. In the case of a *bedridden occupant*, the patient is transferrable on stairs only by means of a firefighter lift, with adequate accessibility.

Noting that the PTAT definition is clearly applicable only to the autonomous occupants capable of self-evacuation, it is proposed to introduce a different term for occupants requiring assistance. PTAT should be replaced by the ***PAL*** time, combining the ***P****reparation time*, representing the time required to prepare the occupant with mobility impairment (or life supporting equipment) for relocation *and* the time and skills required to the ***A****ssisting staff* to establish a communication ***L****ink,* verbal or a visual (e.g., sign language), with an occupant having cognitive or sensory impairments.

R*i*SET requires the application of a computer evacuation agent-based model and reliable information made available in scientific literature or in guidance documents, calibrated with specific occupancy data. These principles have been applied in the worked example in Section 3. It must be emphasized that the literature data are generally restricted to the assessment of *fire* scenarios characterized by tenability conditions based upon *zero smoke exposure* and *tolerable heat exposure* [42]; occupants are considered able to escape under tolerable downward heat radiation as they do in ordinary conditions in a clear and cold air environment.

ASET is generally the result of the *deterministic* analysis of the design fire scenario (or a cluster of fire scenarios), obtained by hand calculations or zone or field computer models of the fire dynamic, incorporating an engineering judgement in case the detection and warning times are based only on human senses and intervention. Where there is no automatic detection (e.g. level A3 alarm system in PD 7974-6), the time to general warning is likely to be long and unpredictable, and might be any time between a few minutes and several hours (in case of smouldering fires) [64].

The life safety performance criterion is associated with the achievement of an absolute target (acceptance concept 'AC3' in PD 7974-7 [71]) translating the limit state for life safety: ASET>RSET *for each individual occupant*, being autonomous or assisted. The 99th percentile evacuation time prediction may be selected as a key parameter to calculate *one* R*i*SET value to be compared with the ASET value corresponding to minimum time in which one occupant could be incapacitated.

The required number of simulations depends on the standard deviation of the ET population and the accuracy required to obtain an estimate of the extreme values of the distribution. The suggested number of simulations reported in literature [38] ranges from 10 to 2000. A dynamic assessment of the behaviour of the ET statistic is recommended to optimize the number of simulations, provided that a suitable convergence methodology is adopted, monitoring the evolution of the sample standard deviation and testing for sample normality.

If the sample evacuation time distribution has a *normal distribution*, the 99th percentile inclusive evacuation time ($i\mathrm{ET}_{99th}$) prediction is best obtained using the upper bounds of the mean (Eq. 3a or Eq. 3c) and standard deviation (Eq. 3d), obtained after performing the MC trials necessary to reach the convergence on the required accuracy on the mean of the ET distribution:

$$i\mathrm{ET}_{99th} = et_{max} + 2.33\ \sigma_{et_{max}} = (\overline{\mathrm{et}}+\Delta_{\mu_{ET}}) + 2.33\ \sigma_{et_{max}} \quad (13)$$

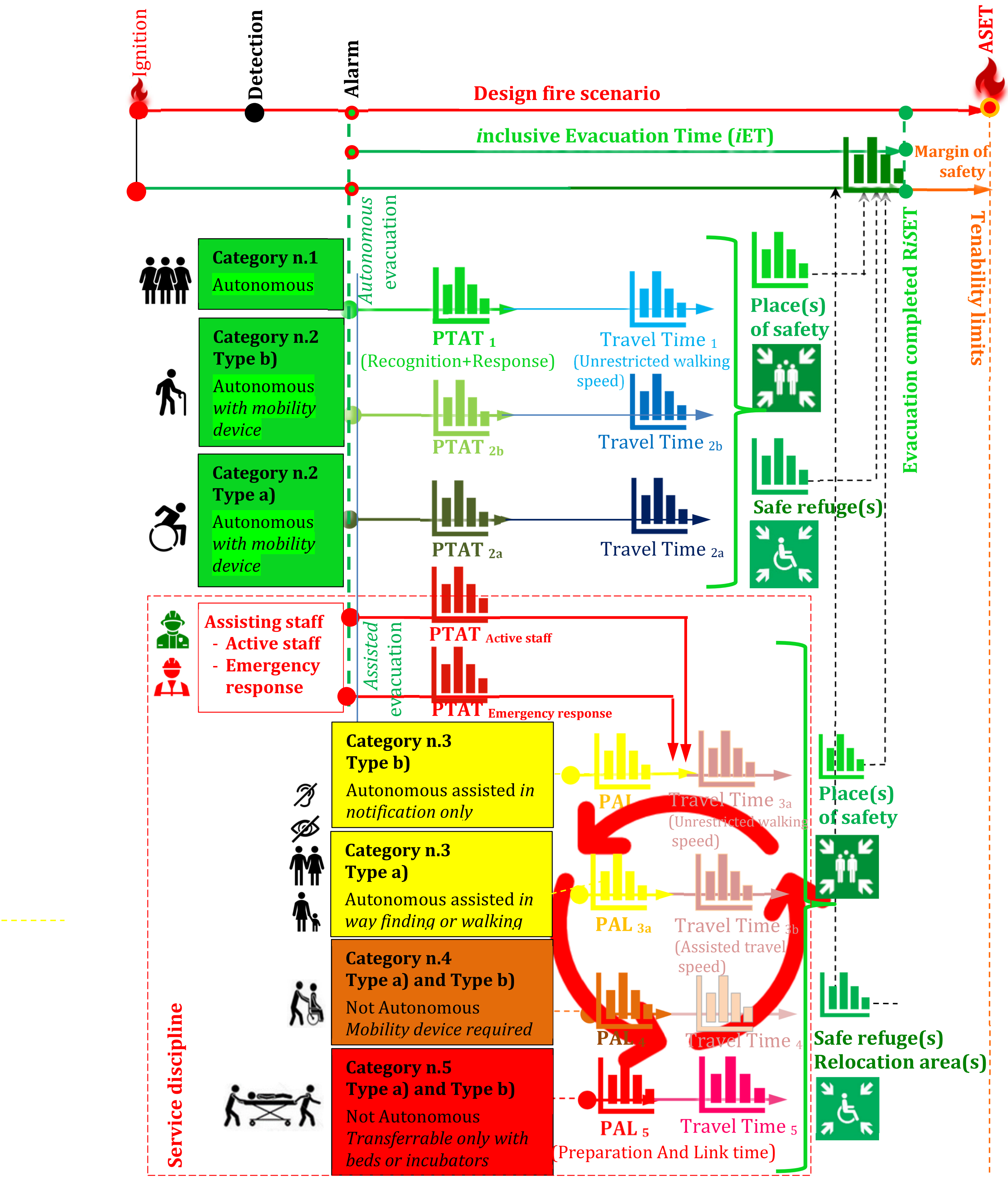


Figure 2: Inclusive approach. The RiSET timeline

3. Results

3.1 Horizontal assisted evacuation of hospital ward combined with the vertical transfer of one In-patient using a firefighter elevator: a case study

It is widely recognized that emergency evacuation in hospitals and care homes is a challenging process that requires a strategy, well-trained staff, and careful execution, as it usually involves vulnerable people with widely varying evacuation capabilities [28, 47, 78]. Researchers have investigated emergency preparedness in health care facilities as a result of a wide variety of natural disasters such as hurricanes [79-80], wildfires [81], earthquakes [82], and bomb threats [83], with a focus on the resilience, e.g. the ability to function and accommodate a massive influx of patients in the immediate aftermath of crisis situations [84-85]. Other studies deal with the issues that a hospital faces when the occupants must be evacuated due to an internal emergency [9, 86-88].

Horizontal assisted evacuation of in-patients, where only the affected ward is cleared of its occupants, is usually required in fire safety codes or regulations [1,13] in order to preserve the hospital functionality. The evacuation process of a medical ward requires as a first step the relocation of the patients to one or more areas of refuge located on the same floor, in accordance with an established emergency actions plan. Table 7 reports the key design prescriptions for existing health care occupancies concerning the horizontal portion of the escape route from Chapter 19 of NFPA 101 [1] and the Italian fire safety regulation [13]. Similar requirements are imposed and both codes are in line with the applicable accessibility regulations.

Table 7: Key prescriptions concerning the horizontal portion of the escape route and relocation areas.

Existing health care occupancies		**NFPA 101 [1]**	**Decree of 19th March 2015 [13]**
Maximum horizontal travel distance to reach an exit or an adjacent fire compartment		46 to 61 m	30 to 40 m
Minimum clear door width in the means of egress		81 cm	90 cm
Minimum clear and unobstructed width in the means of egress from patients sleeping rooms		112 cm	120 cm
Minimum required space in the adjoining compartments for each occupant relocated	In-patients	1.40 m^2 or 2,8 m^2	1.50 m^2
	Other occupants	0.56 m^2	0.50 m^2
Minimum required space in the adjoining compartments for each occupant relocated	In-patients	1.40 m^2 or 2,8 m^2	1.50 m^2
	Other occupants	0.56 m^2	0.50 m^2
Occupant load factor in sleeping departments		11.1 m^2/person	3 persons/in-patient bed

The horizontal assisted evacuation of a ward in a hospital floor combined with the vertical transfer of one in-patient using a firefighters lift is simulated, implementing the occupant profiles with their unrestricted walking speed and travel speed, the pre-travel times and preparation times, and the movement groups described in the Section 2.

A twelve-stories building is here considered as an illustrative example of the proposed methodology. The hospital building 3D model is shown in Figure 3. The application hospital floor plan is the last (10th) floor having a rectangular shape of ~ 912 m^2, with a central lift lobby and two stairs block (S2 and S3). The floor is also served by two additional stairs (S1 and S5), remotely located from each other. It accommodates one ward (W10) of ~ 310 m^2 consisting of 12 patients sleeping rooms (10 double occupancy, 2 single occupancy), 2 nurse stations and 3 service rooms. Each habitable room has a unique exit access door, 85 to 105 cm wide, connected directly to the corridor ~ 60 m long and 330 cm wide (270 cm in the section leading to stairs S1). A meeting room, two lobbies and a lounge are also located in the 10th floor.

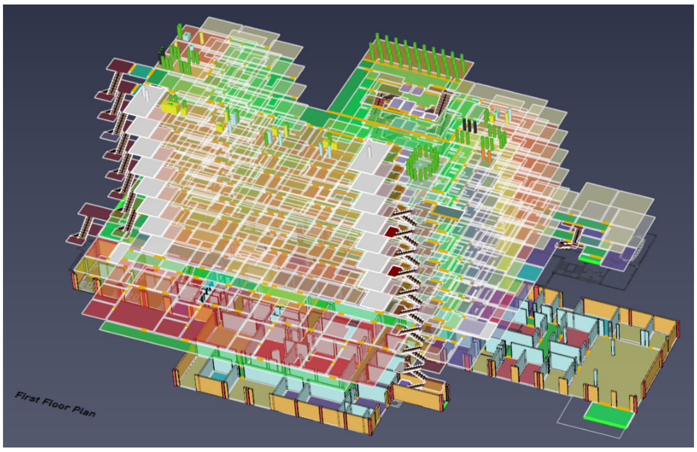


Figure 3: Case study: hospital building 3D model

Figure 4 shows the 10th floor plan with the initial and final occupant positions in the safe refuges (R1&R3 in stair S1, R2 in stair S5). The ward W10 is arranged as a compartment and the evacuation is possible through two exit fire doors ~180 cm wide, leading respectively to the stairs S1 and S5.

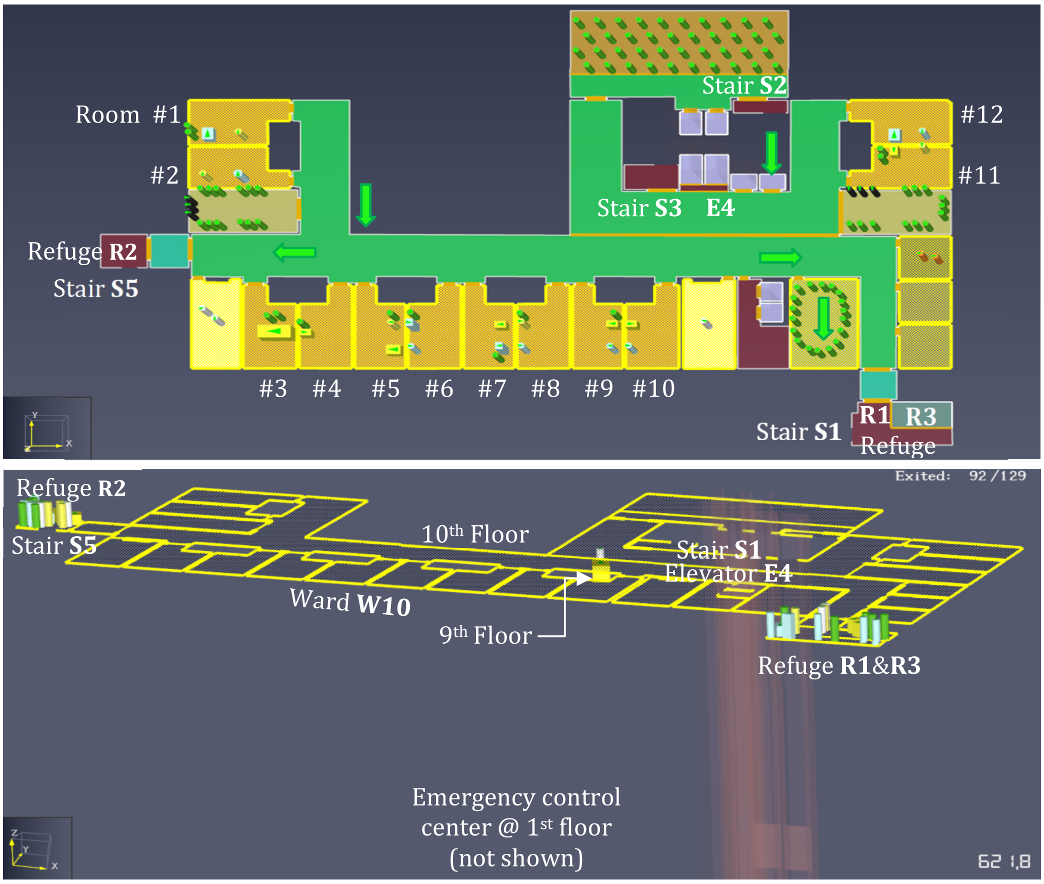


Figure 4: Case study: model plan view with the initial and final positions of the occupants

The two stairwells S1 and S5 allow the building autonomous occupants to reach the exits located on the first floor (level of exit discharge) while their landings are safe refuges to relocate on the same floor a designed number of In-patients. One In-patient in Room #3 is accommodated in the lift landing lobby at the nearest floor level (9th floor) using a firefighters lift.

The Active staff in charge of the assisted horizontal evacuation is formed by the three nurses in staff to Ward 10. Two Emergency responders, coming from the emergency control center located at the 1st floor, have the primary task to vertically evacuate the In-patient located in Room #3 and then support the Active staff operators in relocating the other In-patients, if help is needed.

The number of nurses is determined according to the nurse to In-patients ratio, prescribing how many In-patients each nurse is responsible for during a shift. This ratio is lower for critical care facilities, as patients require more constant monitoring, and is higher long-term care facilities. In Italy, suggested nurse staffing ratio are regulated by law [89]; it is 1 to 6 to 1 to 8 for long-term care facilities and ordinary wards. In this study it is assumed to be ∼ 1 to 7, so that the 22 In-Patients in ward W10 are assisted by 3 nurses. In the scenario examined, it is assumed that 12 Visitors to in-Patients are present in Ward 10 (range: 0 or 1 or 2 Visitors for one in-Patient).

In principle the adequacy of the health care occupancy emergency procedures and means of escape should be demonstrated based on the time of day or night when the evacuation would be most difficult, usually in the night shift when the in-patients are sleeping and fewer staff are present.

Given the objective of this study, it is more interesting to examine day-time visiting hours where the maximum variety of the occupant profiles is observed. The scenario is based on an emergency that occurs in ward W10 on the 10th floor and the safety planning rules the relocation of 21 In-patients in the safe refuges provided in the stair landings S1 and S5. One bedded In-patient in Room #3 is transferred to the nearest floor (9th floor) using the firefighters lift E4. Ten Visitors remain with the in-Patients, while two Visitors are allowed to self-evacuate from the building, together with two Workers present inside the ward W10. Full seating occupancy is assumed in the meeting room (18 occupants), two lobbies (15 occupants each) and a lounge (40 occupants).

The designer should also establish the number of groups initially present that break when the alarm is given. In the scenario investigated, 2 Visitors abandoned the in-Patient they were visiting and self-evacuate. This behaviour has been specified noting that:

- it is usually prescribed in emergency plans that the autonomous occupants not directly involved in firefighting or in evacuation management move to the nearest exit;
- the emergency condition may break the social link with the In-Patient

To summarize, the assisted evacuation concerns 127 occupants in the 10th floor (22 in-Patients; 3 Active staff; 12 Visitors to In-patients; 2 Workers; 88 Autonomous occupants):

- 92 autonomous occupants (2 Workers, 2 Visitors not linked to In-Patients, 88 Autonomous occupants) are instructed to reach an exit at the level of exit discharge (1st floor);
- 21 In-Patients and 10 linked Visitors are relocated in the safe refuges in stair landings S1 and S5, using a variety of mobility devices;
- 1 In-Patient is relocated in the 9th floor;
- 3 Active staff operators are initially in the nurse stations.

The evacuation is conducted with the support of 2 Emergency responders, coming from the emergency control center located in the 1st floor.

To summarize, the sequence simulated corresponds to the following evacuation scheme:

1. Start time is set to the order to relocate all the in-Patients in ward (W10) transferring 21 of them to the safe refuges located in the same floor (stair S1 and S5 landings) and 1 in the 9th floor using the firefighter lift, according to the relocation plan.
2. Active staff operators in charge of the evacuation process are initially inside the ward, in the nurse stations, and collaborate jointly forming a first set of evacuation team.
3. Emergency response operators are initially located in the emergency control center at 1st floor and move to the ward W10, using the firefighter lift, with the task to evacuate the In-patient in Room #3 to 9th floor and then to support the Active staff in the relocation activities.
4. The other autonomous occupants react according to the assigned behavioural instructions, directing to an exit or remaining with an in-Patient, starting an individual or a group movement.
5. After assisting all the in-Patients, the Active staff and the Emergency response operators finally move to the nearest safe refuge in the 10th floor to remain there with the relocated occupants.

The design occupant profiles, initial positions and behaviours are reported in Table 8. Ten movement group schemes are implemented. For each In-patient relocated, it is necessary to specify if assistance is required and the details (*number* and *skills* of assisting operators, use of a *mobility device*).

Table 8: Design occupant initial positions, profiles and behaviours.

Location	Groups	Occupant profile	Behaviour
10th floor Ward W10 (to be evacuated)			
Room #1: In-patient sleeping room	Group 01	1 In-patient Autonomous with manual wheelchair and 2 Visitor to in-patient (duplicate profile for assisted group movement)	• Go To the *specified* Refuge area #02 in stair S5 with initial delay: PTAT (random)
		1 In-patient Assisted Ambulant [1 assistant]	• Wait for assistance of *Active staff team* • Wait the *preparation* time (random) • Go To the *specified* Refuge area #02 in stair S5
Room #2: In-patient sleeping room		1 In-patient Autonomous ambulant with crutches	• Go To the *specified* Refuge area #02 in stair S5 with initial delay: PTAT (random)
		1 In-patient Assisted Ambulant	• Wait for assistance of *Active staff team* • Wait the *preparation* time (random) • Go To the *specified* Refuge area #02 in stair S5
Nurse station #1		2 Staff operators assigned to the Evacuation *Active Staff team*	• Assist *Active Staff team* with an *initial delay* equal to the PTAT (random) • Go To *any* Refuge areas
Room #3: In-patient sleeping room		2 Visitors to in-patient	• Go To any Exit (at 1st floor or ground level) with initial delay: PTAT (random)
		1 In-patient Assisted Vertical Evac bed	• Wait for assistance of *Emergency response team* • Wait the *preparation* time (random) • Go To Elevator E4 [firefighter lift] target: 9th floor • Go To the *specified* Refuge in 9th floor
Room #4: In-patient sleeping room		1 In-patient Assisted Evac chair	• Wait for assistance of *Active staff team* • Wait the *preparation* time (random) • Go To *specified* Refuge area #02 in stair S5
		1 Visitor to In-patient	• Go To specified Refuge area #02 in stair S5 with initial delay: PTAT (random)
Room #5: In-patient sleeping room	Group 02	1 In-patient Assisted Ambulant [1 assistant] and 1 Visitor to In-patient (duplicate profile for assisted group movement)	• Wait for assistance of *Active staff team* • Wait the *preparation* time (random) • Go To the *specified* Refuge area #02 in stair S5
		1 in-Patient Assisted Wheelchair	• Wait for assistance of *Active staff team* • Wait the *preparation* time (random) • Go To *specified* Refuge area #02 in stair S5
Room #6: In-patient sleeping room	Group 03	1 In-patient Autonomous Ambulant with rollator or walking frame and 1 Visitor to In-patient (duplicate profile for group movement)	• Go To the *specified* Refuge area #02 in stair S5 with initial delay: PTAT (random)
		1 In-patient Autonomous Ambulant with walking stick	• Initial delay: PTAT (random) • Go To the *specified* Refuge area #02 in stair S5
Room #7: In-patient sleeping room	Group 04	1 In-patient Autonomous Ambulant with rollator or walking frame and 1 Visitor to In-patient (duplicate profile for group movement)	• Initial delay: PTAT (random) • Go To the specified Refuge area #01 in stair S1
		1 In-patient Assisted Evac chair	• Wait for assistance of *Active staff team* • Wait the *preparation* time (random) • Go To *specified* Refuge area #03 in stair S1

Table 8: Design occupant initial positions, profiles, and behaviours (continued).

Location	Groups	Occupant profile	Behaviour
10th floor Ward W10 (to be evacuated)			
Room #8: in-patient sleeping room		1 In-patient Autonomous	• Initial delay: PTAT (random) • Go To the *specified* Refuge area #01 in stair S1
	Group 05	1 In-patient Assisted Ambulant [2 assistants] and 1 Visitor to In-patient (duplicate profile for group movement)	• Wait for assistance of the *Active staff team* • Wait the *preparation* time (random) • Go To the *specified* Refuge area #01 in stair S1
Room #9: in-patient sleeping room	Group 06	1 in-Patient Assisted Evac chair and 1 Visitor to In-patient (duplicate profile for assisted group movement)	• Wait for assistance of the *Active staff team* • Wait the *preparation* time (random) • Go To the *specified* Refuge area #03 in stair S1
		1 In-patient Autonomous	• Initial delay: PTAT (random) • Go To the *specified* Refuge area #01 in stair S1
Room #10: in-patient sleeping room		1 In-patient Assisted Evac chair	• Wait for assistance of *Active staff team* • Wait the *preparation* time (random) • Go To *specified* Refuge area #03 in stair S1
		1 In-patient Autonomous	• Initial delay: PTAT (random) • Go To the *specified* Refuge area #01 in stair S1
Nurse station #2		1 Staff operator assigned to the Evacuation *Active Staff team*	Same as Active staff in Nurse station #1
Room #11: in-patient sleeping room	Group 07	1 in-Patient Assisted Evac chair and 2 Visitors to In-patient (duplicate profile for assisted group movement)	• Wait for assistance of *Active staff team* • Wait the *preparation* time (random) • Go To *specified* Refuge area #03 in stair S1
		1 In-patient Assisted Ambulant [1 assistant]	• Wait for assistance of the *Active staff team* • Wait the *preparation* time (random) • Go To the *specified* Refuge area #01 in stair S1
Room #12: in-patient sleeping room		1 In-patient Autonomous with electric wheelchair	• Go To the *specified* Refuge area #01 in stair S1 with initial delay: PTAT (random)
		1 In-patient Autonomous	• Go To the *specified* Refuge area #01 in stair S1 with initial delay: PTAT (random)
Service room #1	Group 08	2 Workers	• Go To any Exit (at 1st floor or ground level) with initial delay: PTAT (random)
Meeting room		18 Autonomous occupants	Same as Group 08
Lobby east	Group 09	3 Autonomous occupants	Same as Group 08
		12 Autonomous occupants	Same as Group 08
Lobby west	Group 10	3 Autonomous occupants	Same as Group 08
		12 Autonomous occupants	Same as Group 08
1st floor: 2 occupants (2 Emergency response operators)			
Emergency control center		2 Emergency response operators assigned to the Evacuation *Emergency team*	• Go To Elevator E4 [firefighter lift] target: 10th floor with *initial delay* equal to the PTAT (random) • Assist *Emergency team* • Change profile to *Active staff* • Assist *Active Staff team* • Go To Go To *any* Refuge areas

The total number of assisted In-patients is 10. In this study, a priority list is fixed in the *scheduling policy* of the Active staff team: 1) In-patient in Room #11; 2) In-patient in Room #9; 3) In-patient in Room #7. Pathfinder assigns the task to the required number of assisting operators, having the necessary skills and being available, who are located at the minimum distance from the assisted occupant. If more than one assisting operator is needed, the assisted occupant shall wait for the whole team to

assemble. Assisted ambulant In-patients or those transferred on wheelchair or evac chair or rescue sheet can be serviced only by an Active staff team. The bedridden In-patient in Room #3 to be transferred using the firefighters lift is assisted only by the Emergency response operators, representing their first action to execute. All these specifications define the design *service discipline*. Different assisting team formation and scheduling policies could be adopted, nevertheless the rules here described allows a wide range of evacuation scenarios to be assessed.
The evacuation capabilities and pre-evacuation and preparation times distributions are selected from Tables 3 to 6, while the mobility devices dimensions assumed in this study are given in Table 9, based on manufacturer technical specifications and literature data.

Table 9: Design mobility device dimensions.

Type	**Length**	**Width**
Hospital bed [1]	220 cm	100 cm
Wheelchair [2]	95 cm	75 cm
Walking frame/rollator [3]	50 cm	57 cm
Carry or evacuation chair [4]	77 cm	52 cm
Hand-held stretcher [4]	200 cm	45 cm
Hand-held rescue sheet [4]	200 cm	75 m

[1] Based on catalogue data (“Karismedica” hospital bed)
[2] Based on catalogue data (“Althea” wheelchair)
[3] Based on catalogue data (“Gibermedicali” DM733 walking frame)
[4] Based on Hunt et al. data [29-30].

The model has been implemented in Pathfinder [91], version 2024.1.0813. Since the 2018 release [92], Pathfinder provides a support for assisted evacuation with mobility devices, group movements and refuges (in the “steering mode”). In Pathfinder assistance can be called only by agents with mobility impairments (“clients”). This constraint does not allow a direct codification of the assisted ambulant profile, overcome simulating a “virtual” mobility device, with a polygonal shape resembling a person, and prescribing the number of assistants and their relative position during the service. A “client” instance is activated by the “Wait for Assistance” behaviour action, eventually with the request of a particular set of emergency team, while the availability to act as a member of a particular set of emergency team is activated by the “Assist” behaviour action. Mobility impaired occupants that do not have autonomous movement capability remain in the position where they are left by the assisting team. If the relocation is in a safe refuge, in Pathfinder the impaired person can unduly impede the entry of other occupants or limit the space availability especially if a mobility device, such as a bed or rescue sheet, is required for the transfer. To tackle this issue, specific areas of refuge for assisted non ambulant profiles should be defined, providing at least two virtual doors so that the assisted non ambulant occupant can be allocated properly and the assisting operators can move out without remaining unduly entrapped.

The assisting tasks are the first to be executed. This means that at the start of the simulation all the occupants who need assistance (“clients”) are “rescued” by *all the available assisting occupants,* having the necessary skills, with an *initial time delay* modelling their PTAT. If an occupant needs assistance, collective movement will not start until the assistance team has assembled, and after *the delay* caused by *the preparation phase.* The *preparation phase* duration depends on the assisted occupant’s needs and capabilities. This kind of group will not break until the service is completed leaving the assisted occupant in the safe destination area; hence the requirement in Pathfinder that *all the group members* (excluding the assistants) *must share the same behaviour*.

To implement a movement group scheme which includes an assisted occupant with other autonomous occupants, it is necessary in Pathfinder to “duplicate” the autonomous profiles in their corresponding assisted ambulant profiles, changing the shape attribute, selecting a polygonal form, and defining a mobility vehicle resembling the human body (i.e. an octagon), *with no attached assistant*.

When a group is formed, its movement is mainly controlled in Pathfinder by two concepts: connected state and the option to choose a group leader to be selected from a specific profile. If a group is in a "disconnected" state (e.g., the mutual distance among group members exceeds a prescribed maximum value), occupants with autonomous profiles will walk toward the leader. A group in a "connected" state will move toward the goal dictated by its behaviour and eventually slowdown along the path if they accidentally get "disconnected". In Pathfinder there is no facility to modify the group constitution during the execution of a task.

The basic groups schemes implemented in the simulation model are described in Table 10. Each assisted In-patient transported on a mobility device or assisted ambulant In-patient, by definition requires individual assistance. Thus, a group can include only one assisted occupant with one or more autonomous occupants – the Visitors to in-patients - sharing a social link.

Table 10: Basic movement groups schemes adopted in the simulation of hospital ward evacuation.

a) Movement groups for occupants having autonomous evacuation capabilities
2 or more Visitors to In-patients (or generic autonomous occupants)
2 or more Workers (not in charge of egress assistance)
1 Autonomous In-patient and 1 or more Visitors to In-patient
1 Autonomous but mobility impaired (5 categories) and 1 or more generic autonomous occupants
b) Movement groups for assisted occupants [1]
1 Assisted ambulant and 1 or more Visitors to in-patients (or generic autonomous occupants)
1 Assisted transported on a wheelchair or evac chair and 1 or more Visitors to in-patients
1 Assisted transported with hand-held rescue sheet and 1 or more Visitors to in-patients
1 Assisted transported with hand-held stretcher and 1 or more Visitors to in-patients
1 Assisted transported on a bed and 1 or more Visitors to in-patients

[1] Each group will include in addition the prescribed number and skilled assisting operators.

During the simulation Pathfinder adapt the speeds reported in Tables 3 and 4 depending on the density around the occupant, and, when group movement is considered, also taking into account the constraints imposed on the mutual distance among the group members. When a group is constituted, it moves mainly at the speed of its slowest member. The unrestricted walking speed for the Active staff/Emergency response personnel is therefore used only when the agent is travelling toward an assisted or has completed all the assigned service tasks. In order to allow the Emergency responders to collaborate with the Active staff, in Pathfinder their Behavior shall include the action "Change Profile", after completing the vertical evacuation of the In-patient in Room #3.

The scenario here considered, horizontal assisted evacuation with the aid of mobility devices, including group movements for both assisted and autonomous occupant profiles, combined with the vertical evacuation using the firefighters lift, is very challenging for the designer whatever is the simulation model adopted.

3.2 Monte Carlo simulation results

Using the probability distribution functions list in Tables 3 to 6, initial random realizations of all input stochastic variables (pre-evacuation time, preparation time, unrestricted speed for both autonomous and assisted profiles) are generated. A deterministic calculation is then performed, applying the design behavioural rules specified in Table 8 and the design service discipline, to return a single model output. The outcome of interest is here represented by the time required to relocate 1 In-patient to the 9th floor and 21 In-patients in ward W10 in the safe refuge areas in landing stairs S1 and S5 on the same 10th floor, whose maximum value being the evacuation time (ET).

In order to evaluate the range and the probability distribution functions of ET and of the relocation times, the process is repeated. 142 MC trials were run using Pathfinder to create a dataset, which is analysed in Section 4 to discuss the impact of the number of trials on model predictions. Given the complexity of the scenario investigated, each single run used has been checked to verify that all the agents and the mobility devices act as expected during their travelling paths and do not remain unduly idle or blocked. For the scenario considered, the ET frequency function and its cumulative distribution function obtained are reported in Figure 5. The ET values are in the range 499-805 s, classified as “slow” according to the Life Safety Code © classification [1].

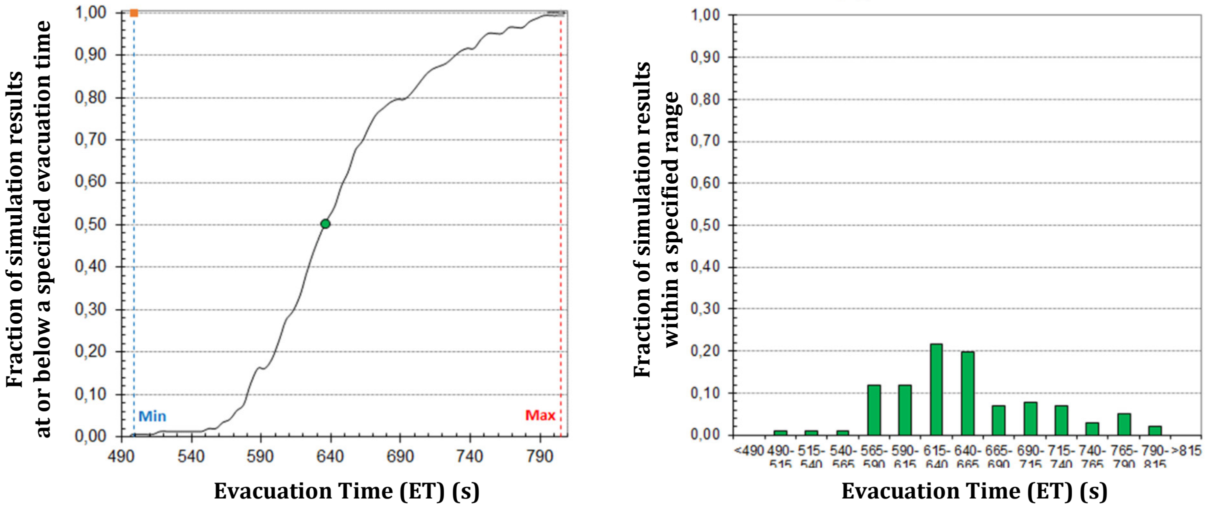


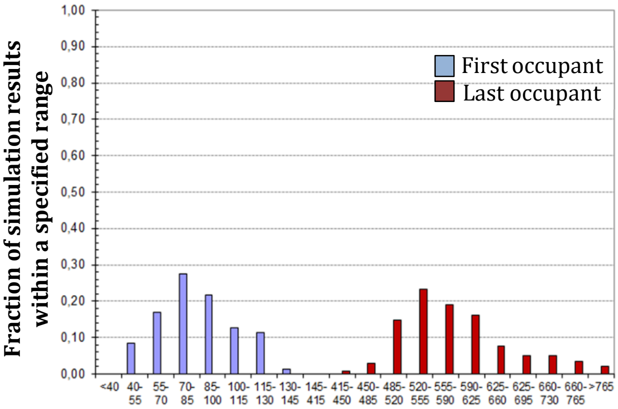
Figure 5: Evacuation time (ET). Statistics based on 142 Monte Carlo simulations

Calculated data have been statistically treated to obtain the histogram plots of the time-series; equally spaced bins (e.g., time interval) are selected to group data, except where a gap clearly separates the first (autonomous) and last (assisted) occupant arrival times. Appropriated bin widths are in the range 5 to 40 s, based on the Rice and the Freedman-Diaconis’ rules [93]. The distributions of the time of arrival of the first and of the last occupant (being the relocation time) are shown in Figure 6 for the safe refuge areas #01 &#03 in stair landing S1 (RT1&RT3) and #02 in S5 (RT2), and the relocation of the bedridden In-patient in Room #3 moved using the firefighters lift in the 9th floor.

The distributions of the time of arrival of the first and of the last autonomous occupant (initially in the two lobbies, in the lounge and the meeting room) to reach the exit at the discharge level (1st and ground floor) is illustrated in Figure 7.

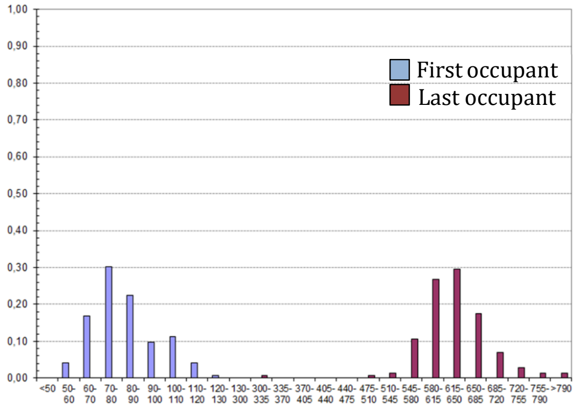
In an assisted evacuation scenario, the key parameters are the number and skills of the assisting staff and the PTAT and preparation times [25, 27-28, 35]. The calculated ET and RT probability distribution functions are determined by the prescriptive rules concerning the service discipline and by the stochastic variables determining the pre-travel activity times and the preparation times, and the unrestricted walking speeds and assisted travel speeds. When examining the simulation results, there are differences both in the order the assisted occupants are served and in the composition of the assisting teams serving each assisted occupant. Statistics are given in the following Table 11 (ET) and Table 12 (RT1, RT2).

When both assisted and autonomous occupants share a common destination, the autonomous occupant profiles, which are not involved in movement group scheme involving an assisted occupant, are the first to arrive and therefore their design characteristics (PTAT and unrestricted walking speed) determine the first part of the usage of the target destination. The flow of the assisted occupants then follows, or is sometimes partially overlapped, depending mainly on the service discipline and the mobility device eventually required for the transferral. Besides the unrestricted speed and the travel path, the queuing for assistance and preparation times of assisted occupants governs the usage of the safe refuge areas.



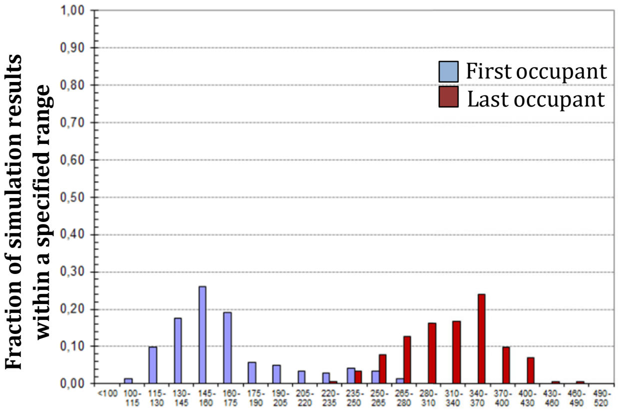
Time of arrival of the first/last occupant (RT2) (s)

a) safe refuge area #02 in stair S5 (4 autonomous In-patients, 3 Assisted ambulant In-patients, 2 Assisted In-patients and 5 Visitors to In-patients)



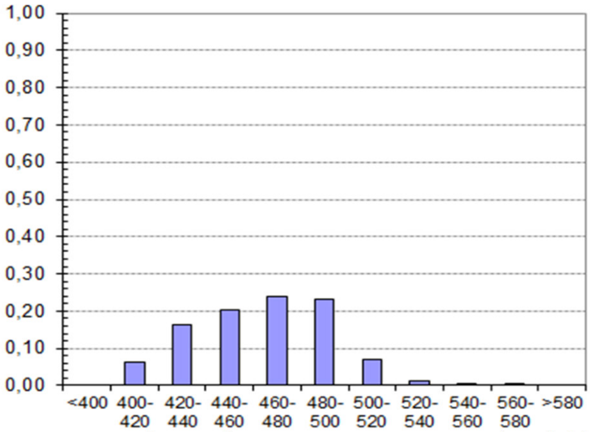
Time of arrival of the first/last occupant (RT1) (s)

b) safe refuge area #01 in stair S1 (6 autonomous In-patients, 2 Assisted ambulant In-patients and 2 Visitors In-patients)



Time of arrival of the first/last occupant (RT3) (s)

c) safe refuge area #03 in stair S1 (4 assisted In-patients and 3 Visitors to In-patients)



Time to relocate the In-patient in Room #3 (RT4) (s)

d) safe refuge area in 9th floor (1 assisted In-patient)

Figure 6: Time of arrival of first/last occupant: a) safe refuge area #02 in stair S5 (4 autonomous In-patients, 3 Assisted ambulant In-patients, 2 Assisted In-patients and 5 visitors to In-patients); b) safe refuge area #01 in stair S1 (6 autonomous In-patients, 3 Assisted ambulant In-patients, 3 Assisted ambulant In-patients and 2 visitors to In-patients); c) safe refuge area #03 in stair S1 (4 Assisted ambulant In-patients and 3 visitors to In-patients); d) 1 assisted In-patients vertically evacuated. Statistics based on 142 Monte Carlo simulations.

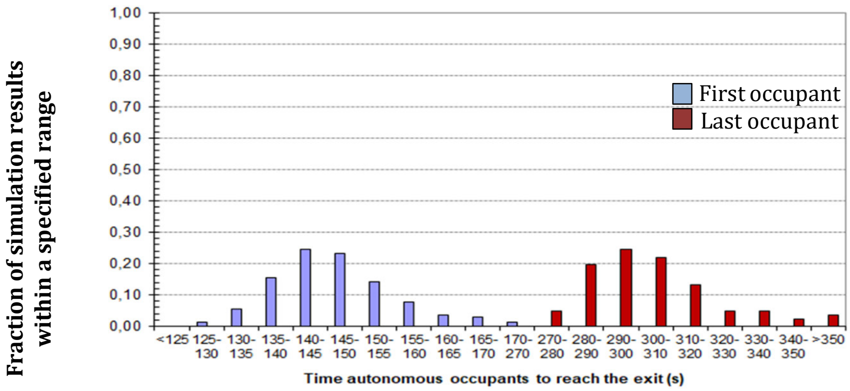


Figure 7: Time of arrival of first/last autonomous occupant to reach the exit (92 occupants). Statistics based on 142 Monte Carlo simulations

4. Discussion

The results of the 142 MC simulations of the assisted evacuation scenario presented in Section 3.2 (Figures 5 to 7) are here analysed applying the principles introduced in Section 2. It is remarked that the stochastics variables are described by probability distributions derived from the statistics given in Tables 3 to 6 (not fictitious ones), including both autonomous and assisted profiles.

4.1 Descriptive statistics

Aggregating the output stochastic variables of interest (the evacuation time: ET; relocation times: RT1, RT2, RT3, RT4) into groups by size and displaying the values as a histogram provides the approximate shape of the probability density function. The output values can themselves be used as an empirical distribution, thereby calculating the percentiles and other statistics. These statistics can then be used for developing confidence bands, as discussed in section 2.5.1; the precision of the expected value of the variable of interest and the distribution shape approximations improve as the number of simulation trials increases as is clearly shown in Figure 8 and Table 11, for ET, Figure 9 and Figure 10 and Table 12, for RT1 and RT2.

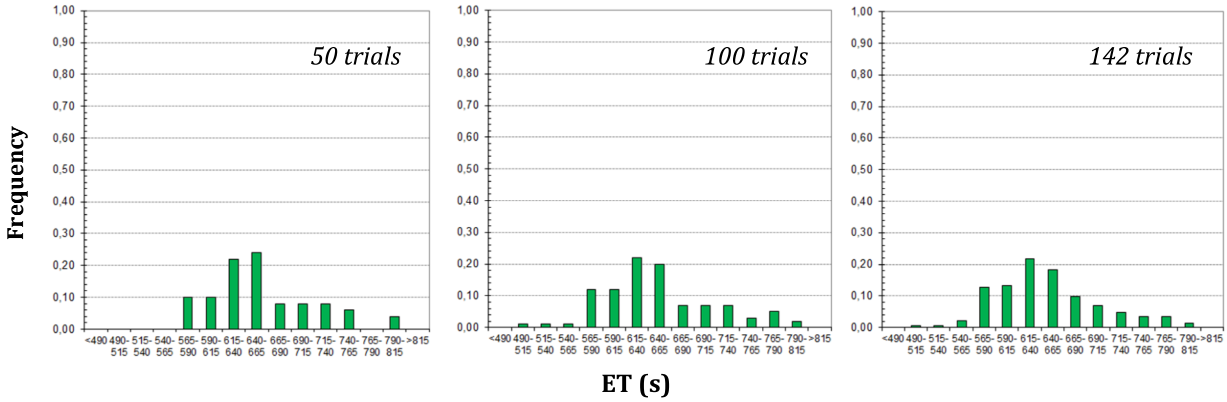


Figure 8: Evacuation time (ET) histograms evolution as a function of the number of Monte Carlo trials

Most results presented in Section 2.5.1 are valid regardless of the shape of the underlying distribution provided that the sample is large enough; but the *normality* (or even the *symmetry* in the distribution) make the inferences more robust even in case of small samples [73]. The method can be generalised adopting Bonett [75] confidence intervals with a larger sample size.

Table 11: ET descriptive statistics evolution as a function of the number of Monte Carlo trials

ET statistics		25 trials	50 trials	75 trials	100 trials	125 trials	142 trials
Mean	$\overline{et}$ (s)	648	659	656	651	649	646
Standard deviation	s_{et} (s)	58	55	58	61	58	57
Standard error	$\frac{s_{et}}{\sqrt{n}}$ (s)	11,5	7,7	6,6	6,1	5,2	4,8
95% CI for the mean	$\Delta_{\mu_{ET}}$ (s)	23,7	15,1	13,0	11,9	10,2	9,4
Median	(s)	637	651	649	641	638	637
Minimum	et_{max} (s)	575	575	515	499	499	499
Maximum	et_{min} (s)	805	805	805	805	805	805
Range	(et_{max}-et_{min}) (s)	230	230	290	306	306	306
IQR [Q3-Q1]	(s)	50	70	60	68	66	63
Kurtosis		2,2	0,2	0,3	0,2	0,2	0,3
Skewness		1,4	0,8	0,7	0,5	0,6	0,6

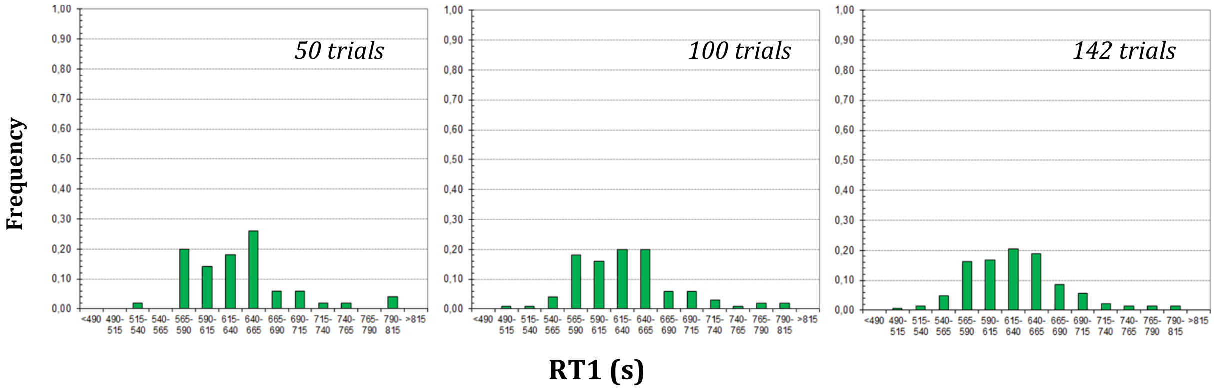


Figure 9: Relocation time in safe refuge area #01 in stair S1 (RT1) histograms evolution as a function of the number of Monte Carlo trials

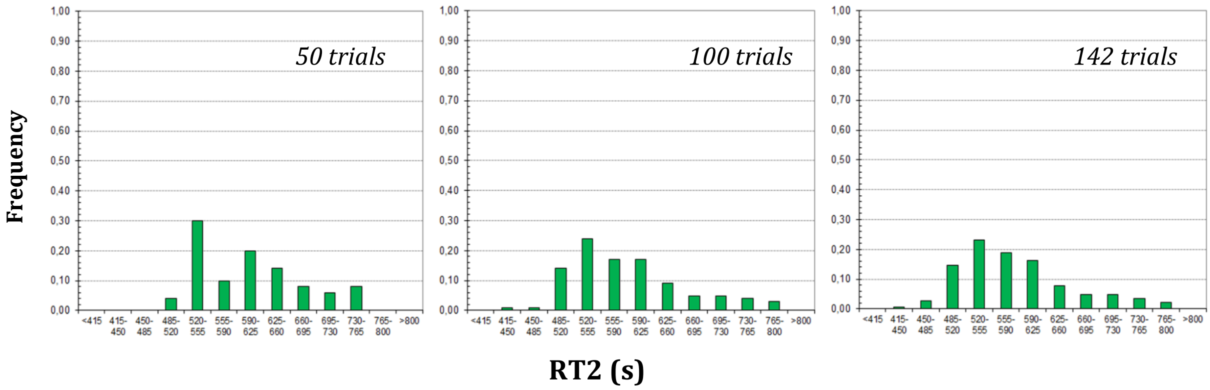


Figure 10: Relocation time in safe refuge area #02 in stair S5 (RT2) histograms evolution as a function of the number of Monte Carlo trials

Table 12: Relocation times RT1 and RT2: descriptive statistics evolution as a function of the number of Monte Carlo trials

RTs statistics	*Relocation time in refuge area #01 in stair landing S1 (RT1)*				*Relocation time in refuge area #02 in stair landing S5 (RT2)*			
	25 trials	50 trials	100 trials	142 trials	25 trials	50 trials	100 trials	142 trials
Mean $\overline{rt}$ (s)	631	637	632	630	584	604	588	583
Standard deviation s_{rt} (s)	63	54	55	52	57	69	76	73
Standard error $\frac{s_{rt}}{\sqrt{n}}$ (s)	12,6	7,7	5,5	4,4	11,5	9,8	7,6	6,1
95% CI for the mean $\Delta_{\mu_{RT}}$ (s)	26,1	15,0	10,8	8,6	23,7	19,2	14,8	12,0
Median (s)	622	628	624	624	563	600	575	569
Minimum rt_{min} (s)	535	535	499	499	494	489	417	417
Maximum rt_{max} (s)	805	805	805	805	711	751	788	788
Range $(rt_{max}$- $rt_{min})$ (s)	270	270	306	306	217	262	371	371
IQR [Q3-Q1] (s)	122	66	66	64	140	97	95	89
Kurtosis	2,4	1,8	1,1	1,1	-0,6	-0,6	0,2	0,3
Skewness	1,5	1,1	0,8	0,8	0,6	0,5	0,7	0,7

A *normal* probability plot (NPP) or a quantile-quantile plot (QQP) should be constructed for each random output variable of interest. Deviation from a straight line indicates that the population distribution is not normal. If the NPP or QQP indicates normality, one of the statistical tests for normality can then be performed to *quantify* the confidence level of a normality assumption. The Shapiro-Wilk test and the D'Agostino-Pearson test have been selected due to their best global performance compared to other normality tests [94]. Both tests confirmed that the normal distribution model does not fit the ET observations. However, the magnitude of the difference between the sample distribution and the normal distribution is small, as shown in Figure 13.

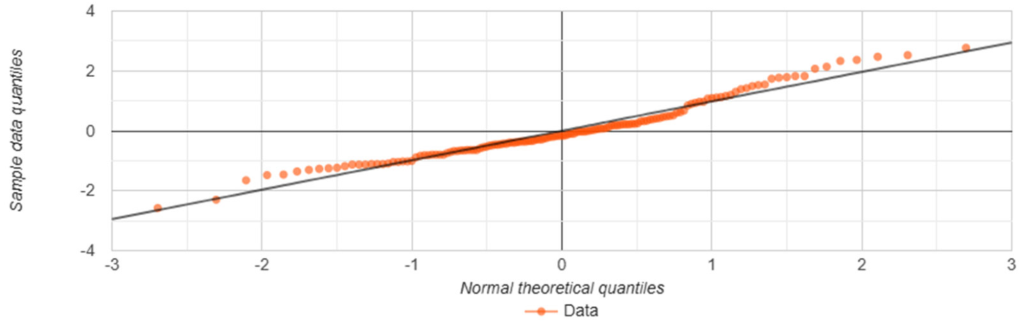


Figure 13: Evacuation time (ET) QQ-Plot for a sample of 142 Monte Carlo trials

4.2. Convergence analysis and accuracy

The application of the methodology presented in 2.5.1 to estimate and update the number of trials that is needed to achieve a certain level of precision is applied to the worked case. The design basis are: $\Delta_{\mu_{\mathrm{ET\ design}}}$ = 10 s, α = 0.05, n_{min} = 40, N=$n_{\max}$=142. The evolution of the minimum, maximum, average and standard deviation of the ET distribution as a function of the MC number of trials is illustrated in Figure 14, while Table 13 reports the evolution of the half-width of the confidence interval and the inference on the total number of simulations required to obtain the design accuracy.

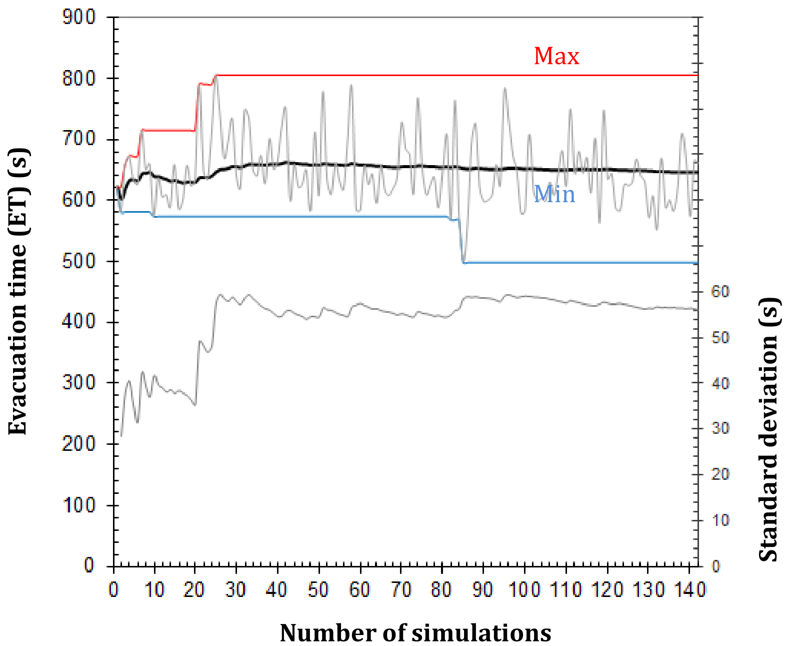


Figure 14: Evacuation time (ET) average ($\overline{et}$) and standard deviation (s_{et}) evolution

Table 13 Evacuation time (ET) convergence as a function of the Monte Carlo number of trials (design basis: $\Delta_{\mu_{ET\ design}}$=10 s, α = 0.05)

ET	n_1 =10	n_2 =40	n_3 =70	n_4=100	n_5=130	n_{max}=142
$\bar{\text{et}}$ (s)	640	649	656	652	649	647
s_{et} (s)	42	55	55	59	57	56
$\Delta_{\mu_{ET}}$ (s)	29.9	20.8	13.0	11,6	9,7 (< $\Delta_{\mu_{ET\ design}}$)	9.2
$n_{\mu_{ET}}$	89	114	117	137	125	123
Normal distribution					No	

After conducting 10 runs (n_1 = 10), the first estimates of the mean ($\overline{et}^{10}$= 640 s) and of the standard deviation (s_{et}^{10}=42 s) of the ET distribution are obtained. Using the *t* distribution values, the CI for the mean ($\Delta_{\mu_{ET}}^{10}$=29.9 s) and the first estimate of the total required number of trials ($n_{\mu_{ET}}^{n_1}$=89) are calculated, thus completing the "prediction" step. After performing an additional round of 30 simulations (n_2 = 40 trials), the sample mean ($\overline{et}^{40}$=649 s) and standard deviation (s_{et}^{40}=55 s) of ET are recalculated and its descriptive statistics is obtained and tested for *normality*. Using the *z* statistics, the updated accuracy is $\Delta_{\mu_{ET}}^{40}$= 20.8 s and the corrected estimate of the number of trials is now $n_{\mu_{ET}}^{40}$=114. This is the first "correction" step. As the convergence termination condition is not verified, additional rounds of 30 runs are executed repeating the process. When a sample of n_5 = 130 trials, the termination criteria is verified as expected: $\Delta_{\mu_{ET}}^{130}$= 9.7 s <$\Delta_{\mu_{ET\ design}}$ and n_4 > $n_{\mu_{ET}}^{130}$=123. The analysis is extended to 142 runs to confirm the convergence. The ET distribution is *not normally* distributed, even if the magnitude of the difference is small, reflecting its dependency on the service discipline and the preparation time distributions. In this case the statistical inference provides the designer a rough estimate of the accuracy of the ET achieved when the proposed termination criterium is reached.

The same convergence and accuracy analysis has been conducted for the relocation times. Details are omitted in this paper.

If the design basis specifies the same accuracy (e.g., Δ and α) for all the stochastic variables of interest (in our case ET, RT1&RT3, RT2 and RT4), the one having the higher standard deviation, *whatever is the mean value*, is the controlling parameter in determining the number of MC simulations required. Stochastic convergence of the evacuation time, which is based on the last service completion or the last autonomous occupant exit, *does not guarantee* the convergence of the relocation times stochastic distributions *within the same design accuracy* (e.g., Δ and α), even if these tasks are completed at an earlier time.

Noting that the sample evacuation time distribution has only a slight deviation from the *normal distribution,* using the results for 130 runs reported in Table 13 and the calculated $\sigma_{et_{max}}$ being equal to 64.45, we obtain the inclusive evacuation time applying Eq. 13:

$$i\text{ET}_{99\text{th}} = (\bar{\text{et}}+\Delta_{\mu_{ET}}) + 2.33\ \sigma_{et_{max}} = (649+9.7) + 2.33*64.45 = 809.1 \text{ s} \quad (14)$$

in line with the maximum sample value of 805 s, observed after having performed 142 trials.

5. Conclusions

The inclusion of mobility, sensory or cognitive impairments in evacuation modelling in a general inclusive framework is proposed to establish a standard codification of the occupant profiles. Mobility is combined with way-finding ability to obtain a basic set of five categories that still retains the potential to describe the performance characteristics of building users and is suitable to be implemented in agent-based computer evacuation models developed over recent years. Apart from occupant characteristics, it is necessary to define the *service discipline*, consisting of three components: the *staff skills and consistency,* the *scheduling policy,* and the *mobility device* eventually required to relocate the assisted occupant. The principles of performance-based *inclusive* design are discussed: a generalization of the conventional RSET is proposed introducing the Required Safe and *inclusive* Escape Time (R*i*SET) criterion. Noting that the conventional PTAT definition is clearly applicable only to the autonomous occupants capable of self-evacuation, it is proposed to introduce a different term for occupants requiring assistance. PTAT should be replaced by the ***PAL*** time, combining the ***P****reparation time and the time and skills* required to the ***A****ssisting staff* to establish a communication ***L****ink,* verbal or a visual (e.g., sign language), with an occupant having cognitive or sensory impairments. While the RSET calculation is traditionally based on deterministic methods, R*i*SET requires a probabilistic risk analysis.

A general procedure based on Monte Carlo methods and the Central Limit Theorem is presented and the convergence scheme and criteria discussed. The number of simulations required for a specified accuracy on the ET distribution is established using a predictor-corrector scheme. A dynamic assessment of the behaviour of the ET statistic is recommended to optimize the number of simulations, provided that a suitable convergence methodology is adopted, monitoring the evolution of the sample standard deviation and testing for sample normality. The 99^{th} percentile evacuation time prediction may be selected as a key parameter to calculate *one* R*i*SET value to be compared with the ASET value corresponding to minimum time in which one occupant could be incapacitated.

The predictive capabilities of the model are applied to the scenario of assisted horizontal evacuation from a hospital ward combined with the vertical transfer of one in-patient using a firefighters lift. Many of the limitations noted in previous studies (Ursetta et al. [34]], Alonso and Ronchi [28]) concerning the use of mobility device and the preparation time for in-patients are overcome. Some difficulties still remain in Pathfinder and require ad hoc adaption and checks [92]: 1) assistance can be called only by agents with mobility impairments; 2) mobility impaired occupants remain in the position where they are left by the assisting team and can unduly impede the entry of other occupants or limit the space availability especially if a bed or rescue sheet is required for the transfer; 3) movement group schemes which include an assisted occupant with other autonomous occupants require to "duplicate" the autonomous profiles involved, defining assisted ambulant profiles with a vehicle shape resembling the human body and no attached assistant; 4) mobility devices like beds or rescue sheets remain sometimes unduly idle or blocked along their travelling path. The proposed model includes all the stochastics variables considered in performance-based design: occupant profiles with their unrestricted walking speed and travel speed, the pre-travel times and preparation times, and the movement groups. Thus, it has sufficient flexibility to be calibrated with site specific data and has the potentiality to be used in emergency planning of assisted evacuation verifying the design service discipline. The results of the model need to be compared to data from actual evacuations as part of a validation exercise before concluding that it gives results that can be used for evacuation planning.

Conflicts of interest
The authors declare no conflict of interest associated with the manuscript.

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