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AGENT BASED MODELING OF META-COMMUNICATION WITH ASSISTED PEOPLE DURING EMERGENCY EGRESS

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ABSTRACT

A few modeling approaches can be used to assess the egress of people having the necessity of being assisted, since both physical and cognitive aspects should be considered. In this study, an agent based approach is adopted with a focus on the behavioral rules assigned to the agents depending on their characteristics and goals. In emergency, while the majority of the agents recognize the risk and starts its egress finding the way-out, the people requiring assistance do not necessarily act in that way. Trained staff operators are required to get in communication with those needing help that could unwillingly remain inside, with meta-communication abilities representing the ways that "link" rescuers and assisted people. A unified framework is proposed to establish a standard codification of the occupant profiles for the purpose to evaluate their evacuation capabilities. Staged evacuation, where only the interested portion of the building or facility is cleared of its occupants, is typically required by fire codes in critical infrastructures before ordering the total evacuation. In health care occupancies the evacuation process of a ward includes often as a first step the relocation of the patients to one or more area of refuges mainly located in the same floor (progressive horizontal evacuation), in accordance with an established emergency actions plan. For this scenario, the approach adopted by the Pathfinder software is compared with the one that is possible to get by coding the design behavioral rules in the NetLogo multi-agent programmable environment, with the latter allowing to model also some basic fire constraints. In Pathfinder each agent can be addressed to a predefined egress route or uses a combination of parameters to select its current path to an exit, such as queue time plus travel time. In NetLogo, each agent way finding strategy has to be coded to follow either the minimum distance or a gradient toward an exit door, which represents an attractor. The agents respond dynamically to environmental changes, such as changing queues or exit door availability, with movement characteristics depending on their profiles, autonomous or assisted by devices like a wheelchair or a stretcher. Speed of movement adapts to the conditions encountered on the means of egress leading toward their goal (i.e. reach an exit door, set a link with the assisted and direct to a safe area). Group movement can be simulated in both platforms to reproduce the link between the patients and their visiting friends during the evacuation process.

1. INTRODUCTION

Life safety in buildings and its technical requirements respond to a wider range of concerns beyond fire hazards, including crowd safety, thus contributing to an ordered and controlled movement of people in emergency conditions that require to decide in advance where people can be safely located. Protection of occupants is achieved by the combination of prevention, protection, egress, and other measures. When designing the method of evacuation, all forms of egress should be considered, including the appropriateness of the use of an elevator evacuation system, specifically designed to provide protection from fire effects so that it can be used safely for egress. The capabilities of the staff assisting in the evacuation process should also be considered.

Life safety goals and objectives shall be met with due consideration for the occupancy functional requirements, reducing the need for total occupant evacuation, especially in buildings and facilities which accommodate persons who are mostly incapable of self-preservation due to their age or physical/mental disability, and sometimes are confined in locked rooms or wards. In this kind of occupancies areas of refuge are usually required to give a temporary shelter during egress especially for those requiring assistance: they serve as staging areas that provide relative safety to a predefined number of occupants while other activities are begun, providing a phase of the total egress process from the immediately threatened area and the evacuation to a public way. An area of refuge might be another building connected by a bridge, a compartment of a subdivided story, an elevator lobby or an enlarged story-level exit stair landing, usually accessible by means of horizontal travel complying with the accessible route requirements foreseen in the national building regulations and standards (i.e. ICC ANSI A117.1 (2017), Decree of the Italian Ministry of the Public Works (1989)).

Fire safety regulations provide prescriptive guidance concerning the means of egress and the evacuation strategy. Provision of refuge or evacuation facilities, or both, staff reaction and preparedness, and notification and communications systems to occupants are key elements to be considered, especially in establishments such as health and day care facilities where there are likely to be many persons to be assisted in an emergency situation (i.e. NFPA 101 (2018) "Life Safety Code", Decree of the Italian Ministry of the Interior dated 19 March 2015).

A full review of egress models is given for instance by Kuligowski et al. (2010, 2016) or Vermuyten et al. (2016) and unveils that most published studies are focused on the self-evacuation process in building or transportation environments. Only few recent studies deal with the numerical simulation of assisted hospital evacuation scenarios (Golmohammadi and Shimshak (2011), Alonso (2014), Hunt et al. (2012, 2015, 2016) with a smaller fraction covering the issue of phased evacuation (Cepolina (2009), Ursetta et al. (2014), Rahouti et al. (2016), Alonso and Ronchi (2016)).

2. OCCUPANT CHARACTERISTICS AND EVACUATION CAPABILITIES

The selection of the occupant characteristics to be used in the egress process modelling is a critical task and shall provide an accurate reflection of the expected population of building users. A large number of factors can influence the basic performance of people, affecting their ability to meet life safety objectives in a given emergency scenario. Four basic characteristics have been identified as sensibility to physical cues, reactivity, mobility and susceptibility to products of combustion. Individual physical (gender, age) and mental capabilities must be combined with social and contextual factors like the condition of being alone or with others, familiarity with the building and participation in emergency training, alertness (SFPE (2003), "Engineering Guide to Human Behavior in Fire"). The behavior of the occupants will be significantly influenced by whether they are alone or with a group: separated group members are likely, first, 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 of the group while attempting to stay together in close proximity.

Evacuation capability is defined in NFPA 101 (2018) 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 (i.e. an area of refuge). 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 according to the classification of the occupancy or evaluated "experimentally" by a program of drills. Where drills are used in determining evacuation capabilities, translation of drill times into evacuation capability can be operated according to the categories reported in NFPA 101 (2018) document:

- *Prompt*: ability of a group to reliably move to a point of safety in a timely manner that is equivalent to the capacity of a household in the general population (≤ 3 min)

- *Slow*: ability of a group to reliably move to a point of safety in a timely manner, but not as rapidly as members of a household in the general population (>3 min, ≤ 13 min)
- *Impractical*: inability of a group to reliably move to a point of safety in a timely manner (>13 min).

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 (i.e. sign language) communication (Kailes (2011, 2014)), classification as incapable of self-preservation should be considered and staff/emergency response personnel assistance during the egress process should be considered in the emergency plan.
Examples of direct intervention by staff members include carrying an occupant, pushing an occupant outside in a wheel-chair or bed or stretcher, and guiding an occupant by direct hand-holding or continued bodily contact. Occupants disabilities can be classified according to the general categories reported in Table 1, derived from NFPA DARAC (2016), "Emergency Planning Guide for People with Disabilities", noting that 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 (2014)), inspired by the International classification of functioning, disability and health (ICF 2017) developed by the World Health Organization (WHO).

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

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

On these basis, a unified framework is proposed in Table 2 to establish a standard codification of the occupant profiles for the purpose to evaluate their evacuation capabilities. Mobility impairments are combined with way-finding abilities in order to obtain a minimum set of profiles that still retain the potential to describe the performance characteristics of potential building users and is suitable to be implemented in the most recent releases of agent-based egress modelling codes. For each profile, mobility devices and staff assistance eventually required are specified; anthropometric data (i.e. free speed of movement, body shape) may be also considered to introduce further distinction related to gender and age, mainly reserved for the autonomous profiles.
We use the term meta-communication to identify formally the interaction (i.e. set of actions, verbal and visual communication) that is necessary to establish with the assisted in order to include people with disabilities in the egress process avoiding the risk of discriminatory response and failure. As the meta-communication may require specific abilities and training to the care giver, it might be necessary to distinguish in the evacuation instructions the roles of staff employees and emergency response personnel depending on their skills and the characteristics of the assisted people. When a link is established, a group movement shall be considered in modelling the egress, with the care giver acting as a leader with the responsibility to select the exit route.
Finally, it has to be remarked that it is impossible to understand disability without a proper consideration of the building environmental factors (i.e. the locomotive ability of an individual can be enough for moving effectively along corridors or limited inclination ramps but inadequate to descend a stairway) and therefore the evacuation capability assessment shall be properly conducted taking into account both the specific situ and population investigated.

Table 2: Occupants evacuation capabilities framework.

Mobility and way finding capabilities	*Mobility assistive devices*	*Staff/Emergency response personnel assistance*	*Remarks and examples*
1. Autonomous			• *Staff/Emergency response teams* • *Walking patients (priority classification level 4* [1]*)* • *Visitors, occupants* Full way finding capability and ability to independently walk on even and uneven surfaces and negotiate stairs
2. Autonomous with mobility devices	Canes, crutches, walkers, wheelchairs		• *Temporary or permanent disabilities* 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
3. Autonomous requiring assistance in way finding		*1 or 2 staff 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]*)* Able to walk on even and uneven surfaces and negotiate stairs only with the assistance of another person
4. Not autonomous - Major mobility devices required	Wheelchairs, stretchers, rescue sheet, emergency stair travel devices	*1÷4 staff operators for each assisted person*	• *Not autonomous patients (priority classification level 2* [1]*)* *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 firefighter lift (i.e. complying with EN 81-72:2015, clause 5.2.4) accessible for a wheelchair or stretcher (i.e. types 3 to 5 according to EN 81-70:2018)
5. Not autonomous – Transferrable only with hospital beds or incubators.	Beds, incubators	*1 or 2 staff operators*	• *Critical patients (priority classification level 1* [1]*)* Type a): transferrable only on a bed or incubator through an accessible route (for relocation on the same floor) *Type b)*: transferrable on stairs only by means of a firefighter lift (i.e. complying with EN 81-72:2015, clause 5.2.4) with adequate accessibility (i.e. type 5 according to EN 81-70:2018).

[1] Patients priority classification according to the National Association for Home & Care Hospice (2008).

2.1 Occupant profiles and horizontal travelling speeds

The five general profiles reported in Table 2 may originate a number of occupant profiles depending on the occupancy considered. A basic set of *autonomous* profiles that could be involved in the egress process of a hospital ward is reported in Table 3, with the key parameters required to describe the *individual* horizontal evacuation capabilities, where population density is reportedly not a factor.

Table 3: Basic evacuation capabilities matrix for agents with autonomous profiles for a hospital ward during day-time visiting hours.

Autonomous occupant profile	*Unhindered walking speed (m/s) (on level terrain, straight-line)* – *Distribution law*: *Type*	*μ*	*σ*	*Min*	*Max*	*Social grouping*	*Remarks*
Active staff	Normal [1]	1.35	0.25	$\mu - 2.8\sigma$	$\mu + 2.8\sigma$	Individual or assistance team member	Familiar & Trained
Emergency response	Assumed equal to Active staff					Individual or assistance team member	Familiar & Trained
Visitors to in-patients (or generic occupants)	Normal [2]	1.20	0.20	$\mu - 3.0\sigma$	$\mu + 3.0\sigma$	Individual or families possibly linked to one in-patient	Uncertain familiarity & Not Trained
Workers (not in charge of egress assistance)	Assumed equal to Visitors to in-patients					Individual or with co-workers	Familiar & Trained
Autonomous in-patients	Normal [3]	0.95	0.32	$\mu - 2.2\sigma$	$\mu + 2.2\sigma$	Individual or linked to Visitors	Uncertain familiarity & Not Trained
Autonomous but mobility impaired [4]: *Crutches*	Normal [3]	0.94	0.30	$\mu - 1.0\sigma$	$\mu + 1.4\sigma$	Individual or linked to visitors	Uncertain familiarity & Not Trained
Autonomous but mobility impaired [4]: *Walking stick*	Normal [3]	0.81	0.38	$\mu - 1.4\sigma$	$\mu + 2.0\sigma$	Individual or linked to visitors	Uncertain familiarity & Not Trained
Autonomous but mobility impaired [4]: *Rollator or walking frames*	Normal [3]	0.57	0.29	$\mu - 1.6\sigma$	$\mu + 1.6\sigma$	Individual or linked to visitors	Uncertain familiarity & Not Trained
Autonomous but mobility impaired [4]: *Electric wheelchair*	Constant [3]	0.89				Individual or linked to visitors	Uncertain familiarity & Not Trained
Autonomous but mobility impaired [4]: *Manual wheelchair*	Normal [3]	0.69	0.35	$\mu - 1.6\sigma$	$\mu + 1.9\sigma$	Individual or linked to visitors	Uncertain familiarity & Not Trained

[1] Based on Alonso and Ronchi (2016) averaged data for health care staff members. Data differentiated for gender are available in the IMO (2007) "Guidelines for Evacuation Analysis for New and Existing Passenger Ships", 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 (1987) averaged data (all age classes and gender); similar values are reported in Boyle (1999). A constant speed of 1,19 m/s is proposed in the SFPE (2003) "Engineering Guide to Human Behavior in Fire.

[3] Based on Boyle (1999) data.

[4] A simplified approach is proposed by Alonso (2014, 2016) with a unique profile, assuming a uniform distribution of velocities in the range 0.84÷1.40 m/s.

A comprehensive literature review of unassisted movement speeds for people with disabilities is available in the SFPE (2016) "Handbook of Fire Protection Engineering" or in Appendix G of ISO/TR 16738 (2009). 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 emergency response personnel, which are the profiles in charge of the assistance tasks. It is convenient to discriminate between Active staff and Emergency response personnel profiles as will be discussed later in order to prescribe different set of rules concerning the use of the means of egress (i.e. elevators) or specialized assisting skills through the assignment to different emergency teams.
The key parameters required to describe the horizontal evacuation capabilities of *assisted* agents are reported in Table 4. The assisted ambulant profile applies not only to in-patients but also to occupants with cognitive or sensory impairments requiring help in the egress. It is assumed that a constant (but variable for each assisted profile) number of assisting operators performs both the preparation phase and the transportation phases. This constraint is necessary to implement the model in PathFinder and avoid discriminating the staff assignments for the preparation and transport phases for each assisted profile. The total number of assisting operators and their relative position is prescribed in PathFinder in the section describing the mobility vehicle shapes. In NetLogo a "virtual" space of size corresponding to the mobility device can be assigned to the agent.

Table 4: Assisted occupant profiles and travel speed in the horizontal egress process.

Assisted occupant profile	*Assisted travel speed (m/s) (on level terrain, straight-line)*					*Active staff/ Emergency response assignment*
	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 Boyle (1999) data.
[2] Based on Alonso (2014, 2016) data (minimum and maximum values assumed). Some data for evacuation and carry chairs transportation are available in Hunt (2015, 2016).
[3] An additional operator may be needed to prepare the patient for transportation or assist along the travel path.
[4] Based on Hunt (2012, 2015, 2016) overall data, discarding gender differentiation.
[5] Could be reduced to two operators only to execute the task to prepare the patient for transportation.

As PathFinder currently allows to assist only mobility impaired occupants (i.e. those transported with the aid of a mobility device like a wheelchair or a bed), in order to implement the assisted ambulant profile is necessary to define a "virtual" mobility vehicle with a polygonal shape (like an octagon) resembling the cylindrical one that models in this software the human body with the attached number of assistants. This procedure will cause a warning for the concerned occupants but will not impede the simulation to run as expected.
PathFinder (steering mode) and NetLogo adapt the travel velocities reported in Tables 3 and 4 during the simulation depending on space availability, 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. For the Active staff/Emergency response personnel therefore the unhindered walking speed is used only when the agent is travelling toward an assisted or has completed all the assigned assistance tasks.
Most simulation tools do not account for fatigue effects or model it roughly (i.e. in PathFinder defining a penalty to favor travel path with shorter distances rather than shorter times; in NetLogo using a friction function and/or agent energy level).

2.2 Pre-evacuation times

The pre-evacuation time is defined as the time interval needed for hazard condition recognition (detection and notification) and response. To simplify, we will neglect the time to detection which depends on the specific emergency scenario considered, i.e. the strength of the hazard source and its propagation in the building environment (in the case of a fire scenario being related to the flame propagation and heat and smoke transport, refer to ISO/TS 16733-1 (2015)). The notification time can be estimated according to BS PD 7479-6 (2004) or ISO/TR 16738 (2009). Assuming to deal with an occupancy protected by an automatic detection system throughout the building activating an immediate general alarm to occupants (denoted by A1) this time may be set equal to zero.
The aforementioned technical documents stipulate also that the response time can be represented by a log-normal statistical distribution. As emergency response personnel will perceive and react to the hazard faster than the active staff, shorter pre-movement time parameters is selected for this profile, as shown in Table 5. For well-managed cases (denoted by M1), the emergency responders can be expected to move in a range within 30 seconds and 60 seconds upon receiving a sounder or voice alarm (Gwynne et al. (2012)). All the other occupants having autonomous evacuation capabilities and not linked in a group movement scheme, may be assumed to start their movement within 30 s to 120 s.

Table 5: Pre-evacuation times for awake occupants with autonomous evacuation capabilities.

Autonomous occupant profile	*Pre-evacuation times (s)*					*Remarks*
	Distribution law					
	Type	*μ*	*σ*	*Min*	*Max*	
Active Staff	Log-normal [1]	71	60	30 [2]	246 [2]	Familiar & Trained
Emergency response	Log-normal [3]	43	6.44	30	60	Familiar & Trained
Other autonomous profiles *(Workers, Visitors to in-patients or generic occupants, Autonomous in-patients, Autonomous but mobility impaired)*	Log-normal [4]	62.7	19.11	30	120	Uncertain familiarity & Not Trained & Not grouped with an assisted occupant

[1] Based on Alonso (2014, 2016) data for health care staff (same mean value in Gwynne et al. (2002, 2003)).
[2] Range values derived from Gwynne et al. (2002, 2003).
[3] Based on ISO/TR 16738 (2009) data range for awake&familiar profiles in level M1 occupancies.
[4] Based on ISO/TR 16738 (2009) for awake&unfamiliar profiles in level M1 occupancies.

The preparation times for the *assisted* profiles are shown in Table 6. It represents not only the time required to prepare the patient with mobility impairment for relocation but also the time (and skills) needed to establish a communication link with a person having cognitive or sensory impairments. The timings given are only for guidance and depend on the assisted involved, the staff training and 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 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 (2014, 2016) data.
[2] Based on Hunt (2012, 2015) overall data for carry chair for an assisting team of two health care operators.
[3] Based on Hunt (2012, 2015) overall data, for an assisting team of two health care operators.

2.3 Movement Groups

The nature of the social relationship between the occupant and the surrounding population is among the factors that can influence egress performance. A set of occupants which share an affiliation link, like a family or a visitor to an in-patient, will have a strong tendency to stay together and move as a group sharing their way-finding behavior while travelling toward a common destination. The basic movement groups schemes considered in this study are described in Table 7. For the assisted profiles and for the autonomous in-patients or occupant mobility impaired, it is stipulated that only one agent of that type can be put in relationship with one or more autonomous profiles.

Table 7: Basic movement groups schemes.

Movement groups for occupants having autonomous evacuation capabilities
2 or more Visitors to in-patients (or generic 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 occupants
Movement groups for assisted occupants [1]
1 Assisted ambulant and 1 or more Visitors to in-patients (or generic 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 by default also the prescribed number and skilled assisting emergency operators.

In order to implement in PathFinder the movement group with the assisted occupants, it is necessary to "duplicate" fictitiously the Visitors (generic autonomous occupants) profile changing the shape attribute selecting a polygonal form and defining a "virtual" mobility vehicle like explained previously, with no assisting operator attached to it. Even in this case a warning is generated but it will not impede the simulation to run as expected and the assisted group will include by default also the prescribed number (and type) of assisting operators.
The collective movement in case an assisted occupant is involved will start only upon the emergency team completion (if more than one operator is involved) and after the delay caused by the preparation phase. The team will not break until the service is completed leaving the assisted in the safe destination area; hence the requirement that all the group members (excluding the assistants) must share the same behavior.

Grouped 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 (i.e. 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 behavior and eventually slowdown during the path if accidentally getting disconnected. In PathFinder there is no chance to modify the group constitution during the simulation.
Similar basic rules can be coded in NetLogo, noting that in this case the platform has the potentiality to modify on the run the group composition on the basis of a set of conditional rules (i.e. aggregation with selected occupant profiles, group breakage in case of a member is losing contact).

2.4 Assisted evacuation

The inclusion of the assisted evacuation allows a wide range of scenarios to be investigated, ranging from the entire evacuation to a safe location, for only part of travel path (i.e. an occupant in a wheelchair who only needs assistance to descend stairs) or for a stage of the egress process (i.e. one assisting team moves the assisted occupant to one location where another team is responsible to execute another task). Assisted evacuation is usually modelled as a queueing process where several "clients" (the assisted occupants) request the service of one of the available emergency teams having the necessary skills to help.
A "client" instance is activated in PathFinder by the "Wait for Assistance" behavior 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" behavior action. In an egress process simulation, these instructions are usually the first to be executed for occupants having assisted and assisting profiles meaning that at the start of the simulation all the assisted agents require simultaneously the rescue service which is deployed by all the available assisting occupants with an initial time delay modeling their pre-evacuation activities. Hence the utility to discriminate the care givers on the basis of their skills and therefore define multiple sets of evacuation teams, as exemplified in Table 8 with some detail on possible assigned tasks and restrictions.

Table 8: Example of basic sets of evacuation team profiles.

Evacuation team profiles	*Members profiles*	*Assisted profiles*	*Remarks*
Active staff team	Active staff	Restricted to assisted ambulant and transported on a wheelchair or a bed profiles	Cannot use elevators in emergency and may have restrictions on travel path choice
Emergency response team	Emergency response	All assisted profiles	No restriction in travel path choice and able to use selected elevators in emergency

In dealing with queueing systems it is necessary to define the service discipline. Various scheduling policies can be adopted but usually the following two suffice for egress modelling:

- *Priority*: assisted occupants with the highest ranking are served first;
- *Distance*: assisted occupants closest to a free assisting member are served first.

In the first case it is mandatory to establish an evacuation order list. In both cases, if more than one assisting operator is needed, the assisted occupant shall wait for the team completion. In PathFinder team member selection occurs on the basis of the minimum distance criterium.
Different team formation rules and scheduling policies could be followed nevertheless the basic framework described allows to investigate a wide range of egress scenarios.
A similar approach can be coded in the NetLogo platform (refer to Ponziani et al (2018) for details).

3. ASSISTED HORIZONTAL EVACUATION IN HEALTH CARE OCCUPANCIES

It is widely recognized that emergency evacuation in health and day care occupancies is a challenging process that requires a strategy, well-trained staff, and careful execution as it usually involves assisted people with widely varying evacuation capabilities (Wabo et al. (2012), Kailes (2014), Alonso and Ronchi (2016)). Researchers have investigated emergency preparedness in healthcare facilities as a result of a wide variety of natural disasters such as hurricanes (Cocanour et al. (2002), Castro et al. (2008), Gray and Hebert (2007), Klein and Nagel (2007), Hyer et al. (2009)), wildfires (Barnett et al. (2009)), earthquakes (Schultz et al. (2003), Nagata et al. (2017)), and bomb threats (Augustine and Schoettmer (2005)), with a focus on the resilience of hospitals, i.e. the ability to function and accommodate a massive influx of patients in the immediate aftermath of crisis situations (WHO (2015), Keret et al. (2017)). Fewer studies deal with the issues that a hospital faces when the occupants must be evacuated due to an internal emergency (Taaffe at al. (2005), Childers (2010)).
Staged (or phased) evacuation of in-patients, where only the interested portion of the building is cleared of its occupants, is required by fire codes (NFPA 101, Decree of the Italian Ministry of the Interior dated 19 March 2015) before ordering the total evacuation in order to preserve as much as possible the infrastructure functionality. Hence the evacuation process of a medical ward requires as a first step the relocation of the patients to one or more area of refuges mainly located in the same floor (progressive horizontal evacuation), in accordance with an established emergency actions plan.

3.1 The progressive horizontal evacuation of a hospital ward

In order to explore the predictive capabilities for assisted horizontal evacuation, the egress process from a ward in a hypothetical (but complying with the prescriptions that are internationally applied for existing health occupancies) hospital floor is investigated implementing the modeling framework described in the previous section. The support for assisted evacuation with mobility devices, group movements and area of refuges is introduced in the latest releases of the Pathfinder software. The design behavioral rules and way finding strategies have been also coded in the NetLogo multi-agent programmable environment, that allows to model them with more flexibility, for instance relaxing some basic constraint concerning the travel route choice strategy (i.e. maximum exit visibility distance and occupants range of vision) or dynamically modeling the availability of the means of egress during the timeline of the crisis event (Ponziani et al. (2018)).

3.2 Design basis

A two-stories building is considered here as an illustrative example of the proposed methodology. The application hospital floor plan is derived from Hunt (2016) and has a simple rectangular shape of ~ 720 m^2, with two access doors, remotely located from each other, leading to the lift lobbies and the exit stairs. It is located on the first story and accommodates two wards each of ~ 310 m^2 consisting of 7 patients sleeping rooms (double occupancy) and 1 nurse station, with a unique exit access corridor ~ 30 m long and 275 cm wide. Each habitable room has an exit access door 100÷110 cm wide connected directly to the corridor. Each ward is arranged as a fire compartment and the egress is possible through two exit fire doors ~180 cm wide, leading respectively to one stair and to a central horizontal exit, adjoining the two wards, used to relocate the occupants in case of staged evacuation. The wards corridor on the either sides of the horizontal exit is sufficient to relocate a designed number of in-patients, that can also find accommodation in safe areas in the story-level landing within each exit stair. The two stairwells allow the autonomous building population to reach the emergency exits located on the ground floor.
Table 9 reports some key design prescriptions for existing health care occupancies concerning the horizontal portion of the egress path, extracted from Chapter 19 of NFPA 101 (2018) and the Italian fire safety code (Decree of the Italian Ministry of the Interior dated 19 March 2015). Similar requirements are imposed and both codes are in line with the applicable accessibility regulations.

Table 9: Key prescriptions concerning the horizontal portion of the egress path and relocation.

Existing health care occupancies		*NFPA 101 (2018)*	*Decree 19 March 2015*
Maximum horizontal travel distance to reach an exit or an adjacent fire compartment		46÷61 m	30÷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 adequacy of the health care occupancy emergency procedures and means of egress should be demonstrated based on the time of day or night when evacuation of the facility would be most difficult, such as when residents are sleeping or fewer staff are present. Given the objective of this study, it is more interesting to examine day-time visiting hours assuming the maximum variety of the occupant profiles (being autonomous or assisted). The agent behavior rules set the relocation of all the 14 in-patients in ward W1 in the adjoining ward W2 and in the area provided in the stair landing S1, with some visitors remaining with the in-patient during the egress process and others evacuating the building. The sequence simulated corresponds to the following staged evacuation procedure:

1. Start time is set to the order to relocate on the same floor the in-patients inside one ward (W1), transferring them to the adjoining safe ward (W2) or the in the area of refuge located in the nearest exit stair (S1). In the course of the simulation both egress paths are available and the in-patients in rooms 1 to 4 are transferred toward the stair S1 while the others in rooms 6 to 8 are collected in the corridor of the ward W2, according to the evacuation and relocation plan.
2. Active staff operators in charge of the evacuation process are already gathered in the two wards (in the respective nurse stations) and collaborate jointly, forming a first set of evacuation team.
3. Emergence response operators, initially located in the hospital command center at ground floor, direct to ward W1 and support the relocation activities, forming a second set of evacuation team.
4. The in-patients in ward W2 remain passive in their rooms during the relocation activities.
5. The other autonomous occupants react according to the assigned behavioral instructions, directing to an exit or remaining with an in-patient, starting an individual or a group movement.
6. After assisting all the in-patients, the active staff of the two wards recollect in ward W2 while the emergency response operators proceed to control the evacuated ward W1 and finally direct to the area of refuge in the exit stair S1 to remain there with the in-patients.

The design occupant profiles, initial positions and behaviors are reported in Table 10 while Figure 1 shows the floor plan with the initial and final occupants locations and the safe areas. Ten movement group schemes are implemented. The total number of assisted in-patients is 11 with no priority fixed in the queueing discipline. Assisted autonomous in-patients or those transferred on wheelchair or evac chair or rescue sheet can be serviced by any team (in case more than one assistant is required, a mixed team composition is allowed); the bedridden patients are on duty only of a Staff team.

As the fire doors in the corridor are self-closing (and those in the horizontal exit are not required to swing with the egress travel having the same probability to be crossed in two opposite directions), a wait time is prescribed to simulate the time needed to negotiate the doors. Based on Boyce et al. (1999b) data, a normal distribution with mean 3.6 s and standard deviation 1.3 s is assumed (range: 1.6-10.2 s), independent from the occupant profile which is crossing the doorway.

Table 10: Design occupants profiles, initial position and behavior.

Location	*Groups*	*Occupants profile*	*Behavior*
1st floor Ward W1 (to be evacuated): 34 occupants (14 in-patients; 2 workers; 2 Active staff; 16 visitors)			
Room 1: patient sleeping room	Group 01	2 Visitors to in-patients	• Initial delay: *specified pre-evacuation* time • Goto *any* Exit (at ground level)
		1 Assisted Rescue sheet	• Wait for assistance of *any team* • Wait the *specified preparation* time • Goto the *specified* Refuge areas (in stair S1)
		1 Assisted Ambulant	
Room 2: patient sleeping room	Group 02	2 Visitors to in-patients	Same as Group 01
	Group 03	1 Assisted wheelchair patient and 1 Visitor (duplicate profile for assisted group movement)	• Wait for assistance of *any team* • Wait the *specified preparation* time • Goto the *specified* Refuge (S1 #01)
		1 Assisted Ambulant	• Wait for assistance of *any team* • Wait the *specified preparation* time • Goto the *specified* Refuge (S1 #01)
Room 3: patient sleeping room	Group 04	2 Visitors to in-patients	Same as Group 01
	Group 05	2 Visitors to in-patients	Same as Group 01
		1 Autonomous in-patient	• Initial delay: *specified pre-evacuation* time • Goto the *specified* Refuge (S1 #01)
		1 Assisted Ambulant	• Wait for assistance *any team* • Wait the *specified preparation* time • Goto the *specified* Refuge (S1 #01)
Room 4: patient sleeping room	Group 06	1 Assisted Evac chair patient and 2 Visitors (duplicate profile for assisted group movement)	• Wait for assistance of *any team* • Wait the *specified preparation* time • Goto *specified* Refuge (S1 #01)
	Group 07	1 Assisted Evac chair patient and 1 Visitor (duplicate profile for assisted group movement)	• Wait for assistance of *any team* • Wait the *specified preparation* time • Goto the *specified* Refuge (S1 #01)
		1 Visitor to in-patients	Same as Group 01
Room 5: nurse station		2 Active staff operators assigned to the Evacuation *Staff team* set	• Assist *Staff team* with an *initial delay* equal to the *specified pre-evacuation* time • Goto the *specified* Refuge (W2 #03)
Room 6: patient sleeping room	Group 08	1 Autonomous in-patient and 2 Visitors	• Initial delay: *specified pre-evacuation* time • Goto the *specified* Refuge (W2 #04)
		1 Assisted Evac rescue sheet patient	• Wait for assistance of *any team* • Wait the *specified preparation* time • Goto the *specified* Refuge (W2 #02)
Room 7: patient sleeping room	Group 09	1 Assisted Evac wheelchair patient and 1 Visitor (duplicate profile for assisted group movement)	• Wait for assistance of *any team* • Wait the *specified preparation* time • Goto the *specified* Refuge (W2 #04)
		1 Assisted Evac chair in-patient	
Room 8: patient sleeping room		1 Assisted Evac wheelchair patient	
		1 Assisted Evac bed patient	• Wait for assistance of a *Staff team* • Wait the *specified preparation* time • Goto the *specified* Refuge (W2 #01)
Corridor	Group 10	2 Workers	Same as Group 01
1st floor Ward W2: 16 occupants (14 in-patients; 2 Active staff)			
Room 9: nurse station		2 Active staff operators assigned to the Evacuation *Staff team* set	Same as Active staff in Ward W1
Rooms 10÷16		14 passive in-patients	• Wait
Ground floor: 2 occupants (2 Emergency responders)			
Hospital command center		2 Emergency response operators assigned to the Evacuation *Emergency team* set	• Assist *Emergency team* with *initial delay* equal to the *specified pre-evacuation* time • Goto the *specified* Waypoints in evacuated Ward#1 • Goto the *specified* Refuge in stair S1 (S1 #02)

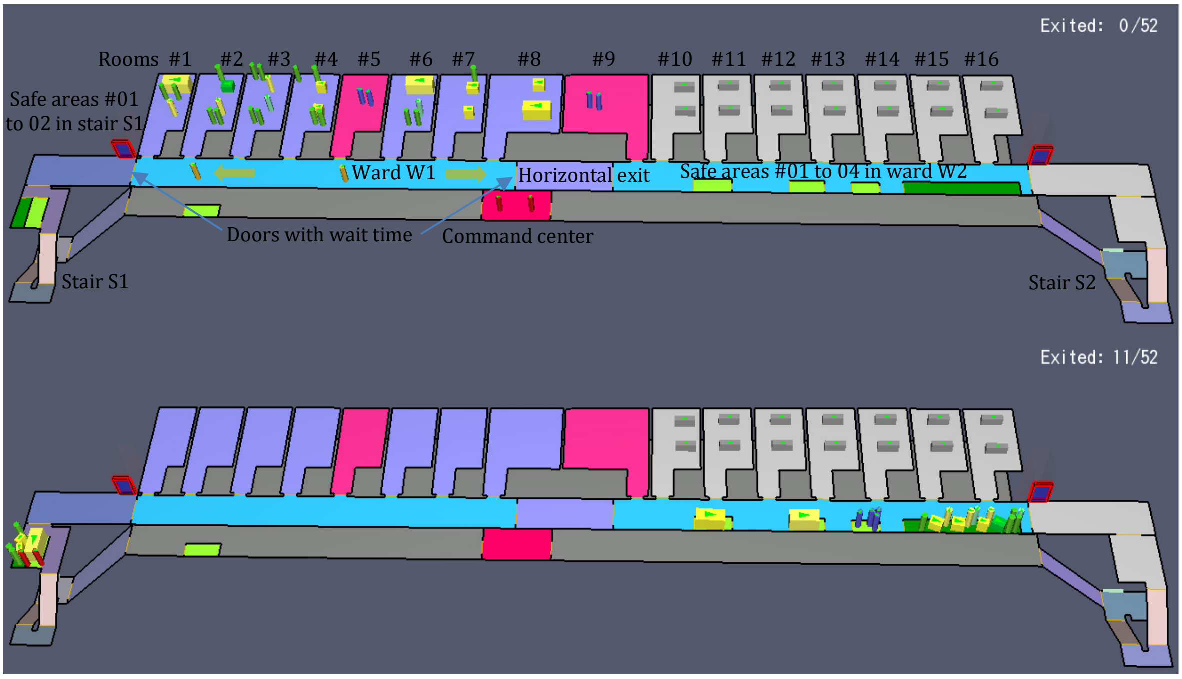


Figure 1: Building plan view with initial and final positions of the occupants.

The evacuation capabilities and pre-evacuation and preparation times distributions are taken from Tables 3 to 6, while the mobility devices dimensions assumed in this study are reported in Table 11, based on available catalogue and literature data.

Table 11: Design mobility device dimensions.

Type	*Length*	*Width*
Hospital bed	220 cm	100 cm
Wheelchair	95 cm	75 cm
Walking frame/rollator	50 cm	57 cm
Carry or evac chair	77 cm	52 cm
Hand-held stretcher	200 cm	45 cm
Hand-held rescue sheet	200 cm	75 cm

4. ANALYSIS AND RESULTS

A total of 25 Monte Carlo simulations were run using the latest PathFinder version available (release 2018.3.0730) in order to consider the variability caused by the use of statistical distributions for each random variable. Other methods might have been used to assess the optimal number of repeated simulations (Ronchi et al. (2014)).

It has to be noted preliminarily that the scenario considered (assisted evacuation combined with complex mobility device like a bed or a rescue blanket with group movements combining assisted and autonomous profiles) is very challenging for the actual software capability. Following key findings are here enlightened and could be addressed in future revisions of the PathFinder algorithm:

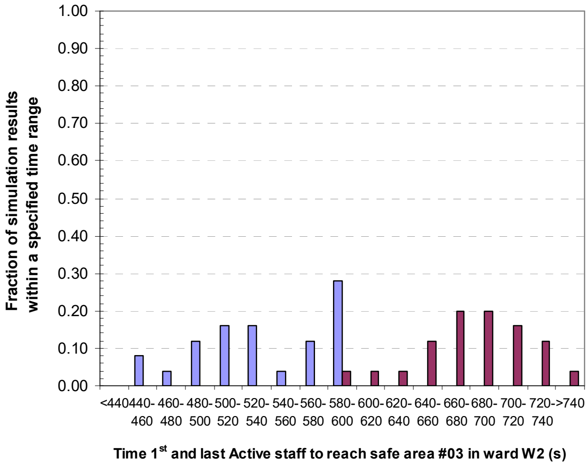
- assistance can be called only by agents with mobility impairments (however this can be solved by simulating a "virtual" mobility device with a polygonal shape resembling a person);
- to implement the movement group with an assisted occupant, it is necessary to "duplicate" fictitiously the generic autonomous occupants profile changing the shape attribute and selecting a polygonal form (a "virtual" mobility vehicle like above, without any attached assistant);

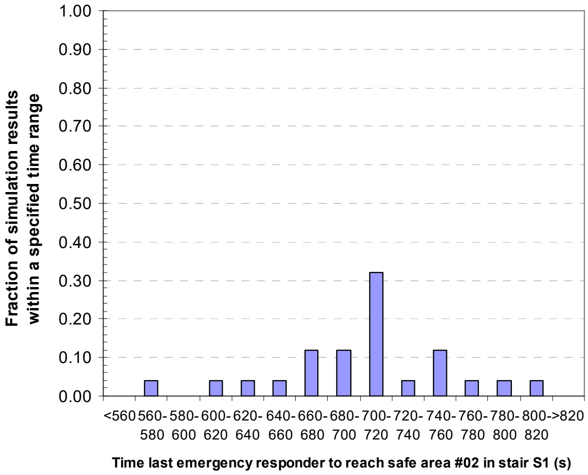
- the refuge area implementation should be improved considering also the peculiarities of mobility impaired occupants:
  1) the total number of occupants that can be allocated in a refuge should be based only on the *effective* number of occupants (being autonomous or with a mobility device). The availability of sufficient space (not considering the assisting operators if they are not planned to remain in that area of refuge) should then be checked issuing an error message in case of violation.
  2) in case more than one mobility impaired person has to be allocated in a safe area (not necessarily a closed room), it could be useful to define "parking" zones and an orientation in order to allow an ordered positioning. Recalling that mobility impaired occupants do not have autonomous movement capability, they remain in the position where they are left by the assisting team and can unduly impede the entering of other occupants following them or limit the space availability if not correctly oriented.
  These issues are particularly relevant for bedridden patients, which are transferred with mobility devices, like a bed or a rescue sheet, having the shape envelope with the maximum size.

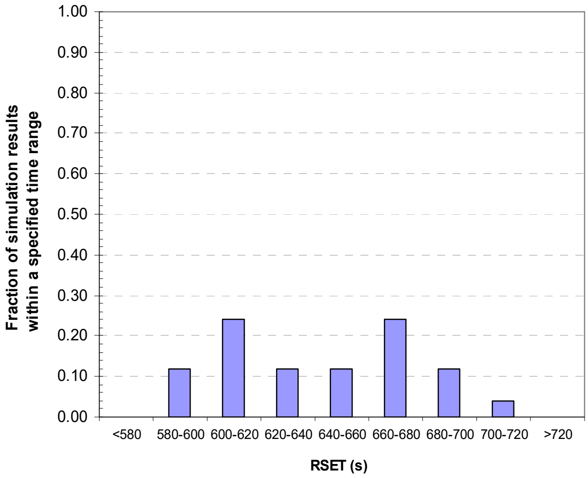
In this study, we introduced the parking zones for bed and evacuation sheets by defining areas of refuge intended for allocating only one assisted occupant, delimitated by two or three fictitious walls defining a space whose dimensions are close to that of the concerned mobility device. Two virtual doors, with different width, are provided so that the assisted can enter through the larger one and one or more assistants can leave out through the smaller one without remaining entrapped.
These limitations precluded the use of the console-based support for Monte Carlo simulation, requiring the control of each single run to verify that all the agents and the mobility devices act as expected and do not remain unduly idle or blocked.
The safe areas usage (time of arrival of the first and last in-patient/visitor), the time necessary for the assisting teams to complete the tasks assigned and the evacuation time for relocating all the in-patients from ward W1 to the safe areas in ward W2 and stair landing S1 (RSET) was statistically treated in order to obtain the mean value, the standard deviation and the histogram plot, as shown in Figures 2 to 3. The results obtained depends clearly on the design basis adopted; in the assisted evacuation process the key parameters are the the staff consistency and skills and the service discipline. Rather than the mean and standard deviation values, it is here more interesting to comment the time distribution in the histograms. The initial part indicates the delay due to the pre-movement activities, followed by a multimodal distribution that reflects the difference in the evacuation capabilities of the population inside ward W1, combining autonomous profiles with those who need assistance, with the bedridden patients being the last to be transferred. More than the unimpeded walking speed and the travel path, the queuing for assistance and preparation times governs the calculated results. The ratio between the minimum and maximum time employed by the last occupant of ward W1 to enter in the planned refuge area is in the range 1:1.50 to 1:2.40.
The RSET has a marked bimodal distribution with a range 581 s to 709 s (ratio 1:1.22), resulting to be "slow" according to the NFPA 101 (2018) classification.

5. CONCLUSIONS

This paper studies the issues concerning the inclusion of mobility, sensory or cognitive impairments in egress modelling. A unified framework is proposed to establish a standard codification of the occupant profiles for the purpose to evaluate their evacuation capabilities. Mobility impairments are combined with way-finding abilities to obtain a minimum set of occupant profiles that still retain the potential to describe the performance characteristics of potential building users and is suitable to be implemented in the most recent releases of agent-based egress modelling codes.
To explore the predictive capabilities for the scenario of assisted horizontal evacuation, the egress process from a ward in a hospital floor is investigated implementing the modeling framework in the Pathfinder software. Many of the limitations noted in previous studies (i.e. Ursetta (2014), Alonso and Ronchi (2016)) concerning the use of mobility device and the preparation time for in-patients have been removed in the latest releases, even if some difficulties still remain.



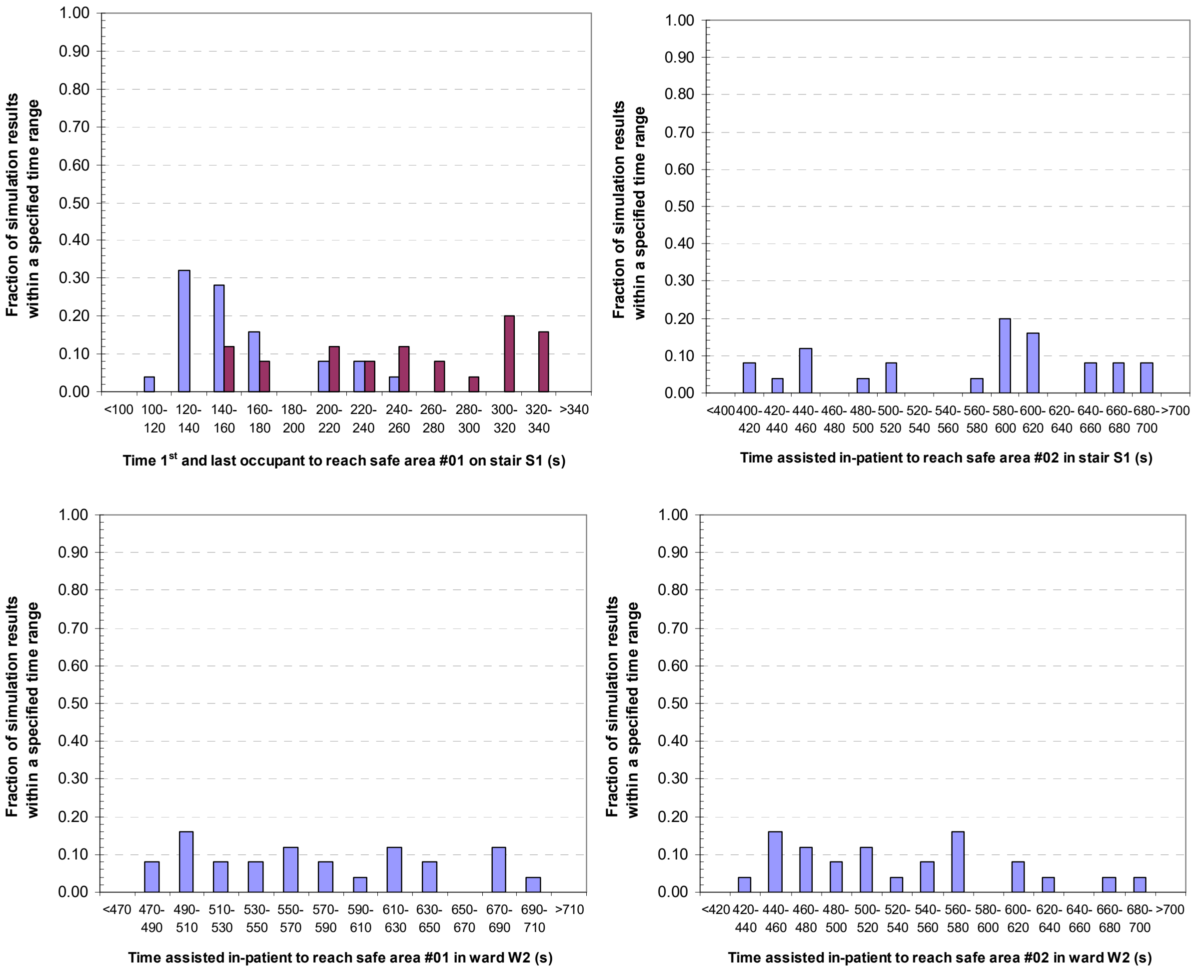


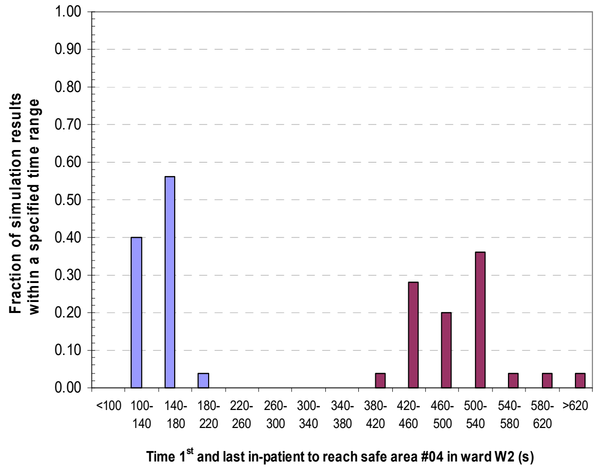


Time (s)	*Active staff* (4 assistants)		*Emergency* (2 assistants)	*RSET*
	Safe area #03 in ward W2		#02 in stair S1	
	First in	Last in	Last in	
Mean	536	680	703	643
Std.deviation	46	39	54	35
Minimum	440	595	576	581
Maximum	595	745	805	709

Figure 2: Time required to complete their tasks by the assisting teams and to relocate the in-patients (RSET) and statistics based on 25 Monte Carlo simulations

A total of 25 Monte Carlo simulations were run to evaluate the variability caused by the use of statistical distributions for each random variable considered (pre-evacuation time, preparation time, unimpeded walking speed for both autonomous and assisted profiles). The results concerning the safe areas usage, the time necessary for the assisting teams to complete the tasks assigned and the evacuation time for relocating all the in-patients (RSET) was statistically analysed. For the design basis considered, the RSET displayed a bimodal distribution with a range 581 s to 709 s.
Implementation in the NetLogo platform resulted more challenging and is still in course mainly to overcome some limitation concerning the space occupancy when mobility devices are considered.
Considering the difficulties in organizing a comprehensive program of drills and exercitations, evacuation simulation can be a valuable tool helping to identify in advance critical issues relating to the adequacy of the staff and of the procedures adopted. The proposed model has sufficient flexibility to be calibrated with site specific data and has the potentiality to be used in emergency planning of assisted evacuation.





Time (s)	*Safe areas in ward W2 (corridor)*				*Stair S1 (landing)*		
	#01	#02	#04 (13 occupants)		#01 (5 occupants)		#02
	First in	First in	First in	Last in	First in	Last in	First in
Mean	576	530	147	494	159	253	563
Std.deviation	67	73	20	59	37	62	92
Minimum	474	437	109	402	117	141	401
Maximum	709	693	182	659	247	339	687

Figure 3: Total safe areas usage (time of arrival of the first and last in-patient/visitor) and statistics based on 25 Monte Carlo simulations.

REFERENCES

Alonso, V. (2014), "Egress Modelling in Health Care Occupancies", *Fire Protection Research Foundation*.

Alonso, V. and Ronchi, E. (2016), "The Simulation of Assisted Evacuation in Hospitals", *Fire and Evacuation Modeling Technical Conference 2016*.

Augustine, J. and Schoettmer, J.T. (2005), "Evacuation of A Rural Community Hospital: Lessons Learned from an Unplanned Event", *Disaster Management & Response*, **3**, 68-72.

Barnett, J., Dennis-Rouse, M. and Martinez, V. (2009), "Wildfire Disaster Leads to Facilities Evacuation", *Orthopaedic Nursing*, **28**, 17-20.

Boyce, K. E., Shields, T. J. and Silcock, G.W.H. (1999), "Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People Moving Horizontally and on an Incline", **35**, 51-67.

Boyce, K. E., Shields, T. J. and Silcock, G.W.H. (1999), "Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capability of Disabled People to Negotiate Doors", **35**, 68-78.

BS PD 7974-6 (2004), "The application of fire safety engineering principles to fire safety design of buildings – Part 6: Human factors. Life safety strategies. Occupant evacuation, behavior and condition".

Castro, C., Persson, D., Bergstrom, N. and Cron, S. (2008), "Surviving the Storms: Emergency Preparedness in Texas Nursing Facilities and Assisted Living Facilities", *Journal of Gerontological Nursing*, **34**, 9-16.

Cepolina, E.M. (2009), "Phased evacuation: An optimisation model which takes into account the capacity drop phenomenon in pedestrian flows", *Fire Safety Journal*, **44**, 532-544.

Childers, A.K. and Taaffe, K.M. (2010), "Healthcare Facility Evacuations: Lessons Learned, Research Activity, and the Need for Engineering Contributions", *Journal of Healthcare Engineering*, **1**, 125-140.

Cocanour, C., Allen, S., Mazabob, J., Sparks, J., Fischer, C., Romas, J. and Lally, K. (2002), "Lessons Learned from the Evacuation of an Urban Teaching Hospital", *Archives of Surgery*, **137**, 1141-1145.

Decree of the Italian Ministry of the Public Works dated 14 June 1989, n. 236, "Technical specifications necessary to guarantee the accessibility, adaptability and usability of private and public buildings in order to overcame and eliminate architectonical barriers".

Decree of the Italian Ministry of the Interior dated 19 March 2015, "Update of the fire prevention technical specifications dated 18 September 2002 for the design, construction and operation of public and private health care occupancies".

EN 81-70 (2018), "Safety rules for the construction and installation of lifts. Particular applications for passenger and good passenger lift. Part 70: Accessibility to lifts for persons including persons with disability".

EN 81-72 (2015), "Safety rules for the construction and installation of lifts. Particular applications for passenger and good passenger lift. Part 72: Firefighters lifts".

Fruin, J. J. (1987), "Pedestrian Planning and Design".

Golmohammadi, D. and Shimshak, D. (2011), "Estimation of the Evacuation Time in an Emergency Situation in Hospitals", *Computers & Industrial Engineering*, **61**, 1256–1267.

Gray, B. and Hebert, K. (2007), "Hospitals in Hurricane Katrina: Challenges Facing Custodial Institutions in a Disaster", *Journal of Healthcare for the Poor and Underserved*, **18**, 283-298.

Gwynne, S., Galea, E.R., Parke, J. and Hickson, J. (2002), "The collection of pre-evacuation times from evacuation trials involving a Hospital Outpatient area and a University Library facility", *Proceedings of the seventh international symposium fire safety science*, 877-888.

Gwynne, S., Galea, E.R., Parke, J. and Hickson, J. (2003), "The Collection and Analysis of Pre-Evacuation Times from Evacuation Trials and Their Application to Evacuation Modelling", *Fire Technology*, **39**, 173-195.

Gwynne, S., Purser, D.A., Boswell, D.L. and Sekizawa, A. (2012), "Understanding and representing staff pre-warning delay", *Fire Technology*, **39**, 173-195.

Hunt, A., Galea, E. R. and Lawrence, P. J. (2012), "An analysis of the performance of trained staff using movement assist devices to evacuate the non-ambulant", *Journal of Fire Protection Engineering*, **22**, 77-99.

Hunt, A., Galea, E. R. and Lawrence, P. J. (2015), "An analysis and numerical simulation of the performance of trained hospital staff using movement assist devices to evacuate people with reduced mobility", *Fire and Materials*, **39**, 407-429.

Hunt, A. (2016), "Simulating hospital evacuation", *Fire and Evacuation Modeling Technical Conference 2016.*

Hurley, M.J. (ed.) (2016), "*SFPE Handbook of Fire Protection Engineering*", 5th ed.

ICC/ANSI A117.1 (2017), "Accessible and Usable Buildings and Facilities".

International Maritime Organization (IMO) (2007), "Guidelines for Evacuation Analysis for New and Existing Passenger Ships".

ISO/TR 16738 (2009), "Fire-safety engineering - Technical information on methods for evaluating behaviour and movement of people".

ISO/TS 16733-1 (2015), "Fire safety engineering - Selection of design fire scenarios and design fires - Part 1: Selection of design fire scenarios".

ISO/TS 29761 (2015), "Fire safety engineering - Selection of design occupant behavioural scenarios".

Johnson, C. (2005), "Using Computer Simulations to Support A Risk-Based Approach for Hospital Evacuation", *Technical Report - University of Glasgow*.

Kailes, J.I. (2011) "Tips for Interacting with People with Disabilities", *Harries Family Center for Disability and Health Policy*.

Kailes, J.I. (2014), "Checklist for Integrating People with Disabilities and Others with Access and Functional Needs into Emergency Planning, Response & Recovery", *Harries Family Center for Disability and Health Policy*.

Keret, S., Nahari, M., Merin, O., Aharonson-Daniel, L., Goldberg, S. and Adini, B. (2017), "Facilitating Emergency Hospital Evacuation Through Uniform Discharge Criteria", *American Journal of Emergency Medicine*, **35**, 681-684.

Klein, K.R. and Nagel, N.E. (2007), "Mass Medical Evacuation: Hurricane Katrina and Nursing Experiences at the New Orleans Airport", *Disaster Management & Response*, **5**, 56-61.

Kuligowski, E.D., Peacock R.D. and Hoskins, B.L. (2010), "A Review of Building Evacuation Models", *NIST Technical Note 1680*.

Kuligowski, E.D. (2016), "Computer Evacuation Models for Buildings", *SFPE Handbook of Fire Protection Engineering,* 2152-2180.

Hyer, K., Brown, L., Christensen, J. and Thomas, K. (2009), "Weathering the storm: Challenges to nurses providing care to nursing home residents during hurricanes", *Applied Nursing Research*, **22**, e9-e14.

ISO/TR 16738 (2009), "Fire-safety engineering — Technical information on methods for evaluating behaviour and movement of people".

Nagata, T., Himeno, S., Himeno, A., Hasegawa, M., Lefor, A.K., Hashizume, M., Maehara, Y. and Ishii, M. (2017), "Successful Hospital Evacuation After the Kumamoto Earthquakes, Japan, 2016", *Disaster Medicine and Public Health Preparedness*, **11**, 517-521.

National Association for Home & Care Hospice (2008), "Emergency preparedness packet for home health agencies".

NFPA DARAC (2016), "Emergency Planning Guide for People with Disabilities".

NFPA 101 (2018), "Life Safety Code".

Ponziani, F.A., Tinaburri, A. and Ricci, V. (2018), "A Multi Agent Approach to Analyse Shift in People Behaviour under Critical Conditions", *International Journal of Safety and Security Engineering*, **1**, 1-9.

Ponziani, F.A., Tinaburri, A. and Ricci, V. (2018), "Modelling Meta-communication: Augmented communication in rescue operation and agent based modelling", *Complex Systems 2018.*

Rahouti, A., Datoussaid, S. and Lovreglio, R. (2016), "A Sensitivity Analysis of a Hospital in Case of Fire", *Fire and Evacuation Modeling Technical Conference 2016.*

Ronchi, E., Reneke, P. A. and Peacock, R. D. (2014), "A Method for the Analysis of Behavioural Uncertainty in Evacuation Modelling" *Fire Technology*, **50**, 1545–1571.

Schultz, C.H., Koenig, K.L. and Lewis, R.J. (2003), "Implications of Hospital Evacuation after the Northridge, California, Earthquake", *The New England Journal of Medicine*, **348**, 1349-1355.

Serra, A. (2014), "Rescue and people with special needs profiling", *International workshop on rescue and people with special needs – Comparing experiences*.

SFPE (2003), "Engineering Guide to Human Behavior in Fire".

Taaffe, K.M., Kohl, R. and Kimbler, D. (2005), "Hospital evacuation: issues and complexities", *Proceeding of the 2005 Winter Simulation Conference*, 943–950.

Taaffe, K.M., Johnson, M. and Steinmann, D. (2006), "Improving hospital evacuation planning using simulation", *Proceeding of the 2006 Winter Simulation Conference*, 509-515.

Thunderhead Engineering (2018), "Pathfinder – Technical reference".

Ursetta, D., D'Orazio, A., Grossi, L., Carbotti, G., Casentini, S. and Poggi, L. (2014), "Egress from a Hospital Ward: A Case Study", *Fire and Evacuation Modeling Technical Conference 2014.*

Vermuyten, H., Beliën, J., De Boeck, L., Reniers, G. and Wauters, T. (2016), "A review of optimisation models for pedestrian evacuation and design problems", *Safety Science*, **87**,167-178.

Wabo, N.C., Ortenwall, P. and Khorram-Manesh, A. (2012), "Hospital evacuation; planning, assessment, performance and evaluation", Journal of Acute Disease, **1**, 58-64

World Health Organization (2015), "Hospital safety index – Guide for evaluators".

World Health Organization (2017), "ICF - International classification of functioning, disability and health".