A SENSITIVITY ANALYSIS OF A HOSPITAL IN CASE OF FIRE
The impact of the percentage of people with reduced mobility and the staff to occupant's ratio

Anass Rahouti, Selim Datoussaïd, and Ruggiero Lovreglio

[1] Civil Engineering and Structural Mechanics Department, Faculty of Engineering, University of Mons
anass.rahouti@umons.ac.be
[2] Civil Engineering and Structural Mechanics Department, Faculty of Engineering, University of Mons
[3] Civil and Environmental Engineering Department, Faculty of Engineering, University of Auckland

Abstract. One of the primary objectives of fire safety is to guarantee the evacuation of all the occupants from a building safely. Although fire safety rules and regulations exist, they remain insufficient to guarantee the safety of all building occupants and do not prevent the dramatic events to be repeated. Especially in health care facilities, e.g. hospitals, care homes, etc., the evacuation procedure is more complex than in an ordinary building. This is due to multiple reasons such as the large number of patients requiring assistance to evacuate or the time required to prepare patients for assisted evacuation. Traditionally, hospitals focused on horizontal evacuation. Patients should initially be moved from areas of risk to safe areas. Furthermore, staff to occupant ratio may be low, especially at night, limiting the ability to instigate a rapid staff response and evacuation of occupants.

Considering the limited number of studies on assisted evacuations, this work aims to provide a deeper insight on the modeling issues to simulate such an event. Based upon a preliminary risk analysis using the Fire Risk Assessment Method for Engineering (FRAME), the most critical floor will be selected and modeled using Pathfinder, an agent-based evacuation model. Furthermore, the impact of different percentage of People with Reduced Mobility will be investigated. Moreover, since the number of staff may significantly vary in the same scenarios (e.g. during the night), different ratios of staff to occupant's will be studied to show the impact of this parameter on the evacuation process.

Keywords: Evacuation Modeling, Assisted Evacuation, Fire Safety, Hospital, FRAME

1. INTRODUCTION

Each year, in Belgium, fire kills and costs money. In fact, in 2013, Belgian fire and rescue services attended over 22.733 fires including 236 in care homes and 79 in hospitals [1]. These fires killed 51 people and injured over 1189 [1]. In health care facilities, patients may start fires, either accidentally or deliberately, particularly by those who are elderly, have learning difficulties, or are young people with disabilities. Those who suffer from mental illness may be particularly prone to starting fires. In these particular buildings, the occupants will be a mixture of patients, staff and visitors. Staff can reasonably be expected to have an understanding of the layout of the premises (or of the part in which they work), while visitors are unlikely to have knowledge of alternative escape routes. Patients may have limited knowledge, but will generally be guided or assisted to a place of safety by staff or visitors. Further to this, health care facilities present a set of challenges from the perspective of fire safety. This is due to multiple reasons such as the large number of patients requiring assistance to evacuate or the time required to prepare patients for assisted evacuation. Furthermore, staff to occupant's ratio may be low, especially at night, limiting the ability to instigate a rapid staff response and evacuation of occupants.

How quickly people can evacuate will depend on their level of reliance on staff and it will therefore be helpful to consider the various categories of patient dependencies: **Independent** (ambulant), the mobility of patients is not impaired in any way and they are able to physically leave the premises without the assistance of staff or, if they experience some mobility impairment, they are able to leave with minimal assistance from another person; **Dependent** (non-ambulant), all patients except those defined as independent or very high dependency. This category also includes children and mental health patients regardless of their independent mobility; **Very high dependency** (non-ambulant), those patients whose clinical treatment and/or condition create a high dependency on staff. This includes those in intensive care/intensive therapy units and operating rooms and those where evacuation would prove potentially life threatening. Patients being cared for in health care premises will vary considerably in terms of mobility and levels of awareness during a fire situation. There may be patients who exhibit severe mobility restriction but will have a good awareness of the situation, being able to co-operate with staff. Others may exhibit normal mobility, but their level of awareness may be such that they present unpredictable behavior (including violent behavior), which may impede staff in an emergency.

It is true that the ideal way to determine the egress time required and the best evacuation strategy would be to conduct some timed evacuation drills involving the movement of all the patients. However, conducting real experiments in health care environments is prohibited since such experiments will be really hazardous in presence of vulnerable people. Another alternative consists on using simulation tools. This would identify many simple problems that may be rectified before any emergency evacuation should occur. In fact, it is well known that evacuation models are powerful tools to study the evacuation process in different scenarios and applications [2–6]. We can find several reviews [2, 3] that show the capabilities and limitations of these types of models. These reviews show that, apart from their possibilities, it is difficult to apply directly the current evacuation models to the scenarios that involve assisted evacuations, due to the presence of vulnerable people who cannot evacuate by themselves (health care facilities, kindergartens and schools). However, few of them are able to simulate assisted evacuations. For example, the EXITT [7] model includes two types of occupants, the able-bodied people and the people with reduced mobility (PRM) in need of assistance to evacuate the building. Decision rules apply only to the first type, and the latter type follows the decisions and movements of their attendants. The BUMMPEE [8] model can simulate the evacuation of people with disabilities, and their interaction with the built environment. However, it is not clear whether this model can simulate assisted evacuations. The buildingEXODUS [9] model includes a theoretical model comprising algorithms derived to represent the use of patient transportation devices during the evacuation process [10]. In addition, there are two models that specialize in the evacuation of hospitals: The G-HES (Glasgow Hospital Evacuation Simulator) [11] and the Assisted Evacuation Simulation System [12]. Both models have been developed to consider assisted evacuations. However, they are not publicly available [13].

Another alternative is the use of other existing evacuation (or general) models that are not explicitly designed to simulate assisted evacuations but they can be flexible enough to archive this goal (e.g. Pathfinder [14], FDS+Evac [15], STEPS [16], etc.). In fact, some of them allow the simulation of additional behaviors, such as travel itineraries assigned to occupants, delays, etc. This could be used to simulate prescript assisted evacuation procedures.

Only a limited number of studies have examined the assisted evacuations using the general models. One of the studies to do so was completed by Golmohammadi and Shimshak [17] showed an analytical approximation to analyze the horizontal and the vertical evacuation times, considering three types of patients. This analytical model permits the user to consider the number and the category of patients and the number of the staff members and the availability of the elevators. Alonso [18] performed an interesting study using STEPS model. She simulated the impact of staff to occupant's ratio on the relocation process of patients on a sleeping room floor in a health care facility. She highlighted the lack of empirical data and the limitations of using a general model for this kind of scenarios, and suggested future development for addressing the problem of simulating assisted evacuations. Ursetta et al. [19] simulated the evacuation process of an Italian hospital ward in case of fire using Pathfinder.

Despite that the modeling of assisted evacuations is restricted, it is commonly agreed that it is needed to differentiate between self-reliant (ambulant) and incapacitated (non-ambulant) patients. Moreover, all the incapacitated patients have a preparation time that may depend on the type of their disability. For some patients, this preparation time will include the processes to stabilize the patient's condition (e.g. operating room), to disconnect the patients from equipment, to move a patient from the bed to a transportation device (e.g. Evac+Chair, stretcher, etc.), to just help them to get dressed or to gather their belongings. Currently, there is a lack of data related to these preparation times and transportation speeds. The values of these parameters are limited. For example, Adams and Galea [20] present an experimental study to evaluate the performance of the movement devices used to assist PRM in high-rise building evacuations. Based on this experimental study, Hunt, Galea and Lawrence [21] conducted a numerical study to analyze the performance of trained hospital staff using movement assist devices to evacuate PRM. Other studies [22, 23] show some possible ranges and values for preparation times considering different types of patients for the sleeping areas.

The study undertaken here aimed (1) to simulate prescript assisted evacuation using Pathfinder; (2) to evaluate the impact of different percentages of people with reduced mobility on the evacuation process, especially on the Required Safe Egress Time (RSET) – the time required by the occupants to leave the floor and escape to a place of reasonable safety; and, since the number of staff may significantly vary in the same scenarios (e.g. during the night), (3) to study the effect of staff to patient's ratio on the evacuation process.

2. METHODS

The methods employed in this study combine risk assessment and evacuation modeling techniques. The initial phase of the study was therefore the use of the Fire Risk Assessment Method for Engineering [24] to identify the most critical floor. Then, the layout of this floor was modeled within Pathfinder using a third-party (PyroSim). And finally, a number of patients with different individual characteristics were created and distributed throughout the model.

When possible, the input of the evacuation model was calibrated using experimental data rather than the default settings of the model. This had the effect of making the evacuation scenarios as realistic as possible.

2.1. FIRE RISK ASSESSMENT METHOD FOR ENGINEERING

The Fire Risk Assessment Method for Engineering developed by De Smet [24], is a comprehensive, transparent and practical calculation method for fire risks in buildings. It is a tool to help a fire protection engineer to define a sufficient and cost effective fire safety concept for new or existing buildings. The FRAME method calculates the fire risk in buildings for the property and the content, for the occupants and for the activities in it. The method is not suitable for open-air environment.

Apart from its use in airports [25], industry [26] and cultural heritage buildings [27, 28] this method has been employed mainly for health care facilities [29, 30].

2.2. PATHFINDER

Pathfinder is an agent-based egress and human movement simulator. It is developed by Thunderhead Engineering. Its purpose is to provide an analytical evacuation tool that could be coupled with an external fire model such as FDS (Fire Dynamics Simulator) [31] to form portion of hazard analysis. The occupants are

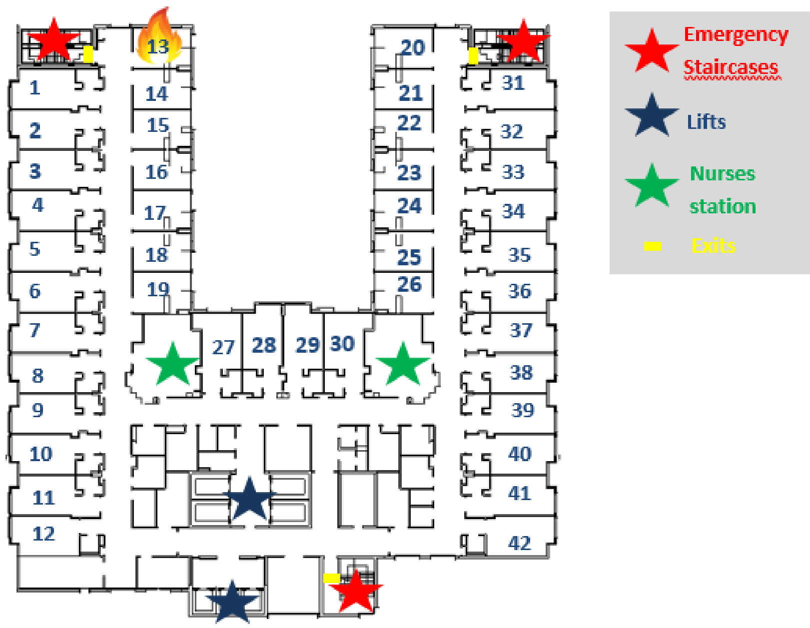

Figure 1. Layout of the 6th floor of the G bloc of the Clinique Sainte Elisabeth

represented as circles moving in a continuous space. It uses two different ways to model the evacuation process (1) and agent-based model (steering) or (2) based on the method of Mowrer ad Nelson (flow model) [32]. The model considers individual profiles (walking speed, delays, etc.) implemented through distribution laws.

3. MODEL CASE STUDY

3.1. FLOOR LAYOUT

The layout of the modeled floor is shown in Figure 1. As shown bellow, this floor contains 42 rooms: 14 single rooms (from 13 to 26) and 28 double rooms (the others). This floor had three exits associated to the emergency staircases, two nurses' stations and some technical rooms. The lifts are not used during the evacuation process. The fire is supposed located in room 13. Therefore, the East Exit is supposed non-functional during the evacuation processes simulated.

3.2. PROFILE OF THE OCCUPANTS

For the simulations, we considered two types of patients: ambulant patients and non-ambulant patients.

For ambulant patients, the movement and behavior of each individual is described by several parameters such as the pre-evacuation time and the horizontal walking speed.

	Mean	St. Dev.	Range
Pre-evacuation time (s) [33, 34]	50.8	-	30 – 66
Horizontal walking speed (m/s) [35]	1.00	0.42	0.10 – 1.77

Table 1. Pre-evacuation time and horizontal walking speed for ambulant patients.

			Mean	St. Dev.	Range
Dependent patients [10]	Evacuation Chair	Preparation time (s)	32.7	5.3	-
		Transportation speed (m/s)	1.46	0.09	-
	Carry	Preparation time (s)	41.5	7.9	
		Transportation speed (m/s)	1.50	0.10	-
	Stretcher	Preparation time (s)	77.7	19.2	-
		Transportation speed (m/s)	1.04	0.09	-
	Rescue	Preparation time (s)	65.2	14.1	-
		Transportation speed (m/s)	0.89	0.24	-
Highly dependent patients [11]		Preparation time (s)	-	-	180-900
		Transportation speed (m/s)	0.40	0.04	-

Table 2. Preparation time and transportation walking speed for non-ambulant patients.

For non-ambulant patients, the movement and behavior of each patient is described by several parameters such as the pre-movement time, which is divided into two components: the waiting time – the time undertaken by the member(s) of staff to reach the room of the patient – and the preparation time – the time undertaken by the member(s) of the staff to move the patient to a wheelchair or to another transportation device. Another parameter is the transportation walking speed – the walking speed of the member(s) of the staff while transporting the patient to another place of safety or while walking with the patients.

The values used for the simulations are shown in the Tables 1 and 2. The waiting times are dependent on the scenario simulated. So, they are not explicitly described here.

There is a lack of data regarding the number of attendants needed to evacuate non-ambulant patients. Table 3 shows some values found on the available literature for dependent patients[10]. As it is shown in this table, the type of the transportation device used defines the number of required attendants to prepare the patient and to assist on the evacuation process. Comparing the different devices, we can conclude that evacuation chair and the rescue sheet require the minimum number of attendants (two).

For highly dependent patients, the number of attendants needed is unknown. Therefore, we suppose that two attendants are enough.

Experiment Phase	Role	Stretcher	Evacuation Chair	Carry Chair (Male)	Carry Chair (Female)	Rescue Sheet
Preparation	Essential	2	2	2	2	2
	Major	1	0	1	1	0
	Minor	1	0	0	1	0
Corridor	Essential	4	1	1	1	2
	Major	0	1	1	1	0
	Minor	0	0	1	2	0
Total number of attendants		4	2	3	4	2

Table 3. The number of operators and their roles for each device.

3.3. EVACUATION STRATEGY

Traditionally, hospitals focused on horizontal evacuation [36]. Patients should initially be moved from areas of risk to areas where a "shelter-in-place" posture can be maintained; usually in separate smoke compartments. As long as it is safe to remain in the "shelter-in-place" position, it is the preferred choice to attempting vertical evacuation. Therefore, in this study, we are only considering horizontal evacuation.

3.4. EVACUATION PROCEDURE

In health care facilities, in case of fire, the objective of the staff is to evacuate as many patients as possible [10, 18]. So, in this study, people in immediate danger are evacuated first, followed by ambulant patients and then non-ambulant patients. For non-ambulant patients, those requiring some transport assistance are evacuated first (wheelchair, evacuation chair), followed by those requiring transport assistance (rescue sheet) and then patients who are being treated and/or would be difficult to evacuate (i.e. Operating Room, ICU, obese, dangerous).

Furthermore, we considered that the attendants use the nearest exit and that only two exits were available.

3.5. SCENARIOS MODELED

Typically, hospital rooms are single or double occupancy but for the hypothetical scenarios simulated, all the rooms are considered as single occupancy. Furthermore, the 42 rooms are considered as fully occupied (see Figure 2).

3.5.1. Scenario 1 All the patients are considered as ambulant. The other scenarios will be compared to this basis scenario.

3.5.2. Scenario 2 A mix of ambulant and non-ambulant patients was considered with different percentages of independent, dependent and highly dependent patients. We considered 6 attendants present to assist on the evacuation of non-ambulant patients. Therefore, three emergency groups were formed by

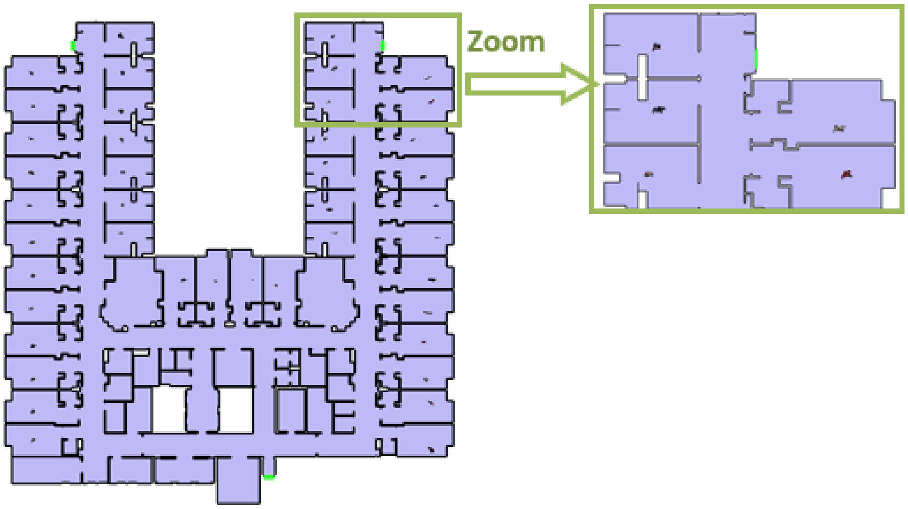

Figure 2. Pathfinder geometry shown with sample occupancy

Sub-scenario	Number of independent patients	Number of dependent patients	Number of highly dependent patients
2.1	28	14	0
2.2	28	7	7

Table 4. Sub-scenarios simulated for Scenario 2

two attendants for assisting each patient. The Table 4 shows the sub-scenarios simulated.

3.5.3. Scenario 3 Like Scenario 2, a mix of ambulant and non-ambulant patients is considered but here the percentage of the patients is constant (1/3 independent, 1/3 dependent and 1/3 highly dependent). In order to evaluate the effect of different staff to patient's ratios on the evacuation process, we considered two different numbers of attendants (nurses): 8 and 12. The Table 5 shows the emergency groups formed for these sub-scenarios.

Sub-scenario	Number of attendants	Emergency groups
3.1	8	4
3.2	12	6

Table 5. Sub-scenarios simulated for Scenario 3

4. RESULTS AND DISCUSSION

4.1. FRAME METHOD RESULTS

The Table 6 presents the results of the Fire Risk Assessment Method for Engineering performed on the G Bloc of the "Clinique Sainte Elisabeth", located at Namur (Belgium). The calculation of the potential risk is carried on each floor of this building but only for the characteristic premises of the floor in question. The method gives the following results: the calculated risk for the property & content (R), the calculated risk for the occupants (R1) and the calculated risk for the activities (R2). For a well-protected compartment, the three values shell be below one.

In general, the results of this analysis demonstrate that the building is well protected (R<1) against fire excluding the technical premise of the 7th floor in which the potential risk for the occupants is greater than one. That conclusion is, in fact, expected since the recent conception of the G Bloc strictly follows the Belgian Prescriptive Codes (AR 6/11/1997).

For the upper floor, the risk for the occupants is important due to the presence of the machinery of the ventilation and heating. In addition, its height makes it difficult to access for firefighters. However, this floor is only accessible for the staff members who are trained to fight the fire.
Since the 7th floor is not accessible to the public and the patients, the most critical floor is the 6th floor in which people could be found during the day and at night.

4.2. PATHFINDER RESULTS

The Pathfinder results have been categorized according to the different scenarios simulated.

4.2.1. Scenario 1 The evacuation curve for the scenario 1 is shown in Figure 3. The mean total evacuation time of ambulant patients is about 383 seconds, with a range of value between 163 seconds and 622 seconds.

4.2.2. Scenario 2 A comparison between the mean evacuation curves of scenarios 1 and 2 is shown in Figure 4. The results demonstrate that there is an increase in total evacuation time when assisted evacuation is performed involving dependent and highly-dependent patients. In fact, for sub-scenario 2.1, in presence of 6 attendants to assist on the evacuation of dependent patients, the evacuation of all the patients takes in average about 483 seconds. For sub-scenario 2.2, in presence of 6 attendants to assist on the evacuation of dependent and highly-dependent patients, the total evacuation takes in average about 2124 seconds.

Comparing the mean total evacuation times of scenarios 1 and 2, one can say that conducting an evacuation in presence of assisted patients takes a higher time than a "normal" evacuation (involving ambulant patients only). This is

		CALCULATION of the POTENTIAL RISKS			CALCULATION of the ACCEPTANCE LEVELS			CALCULATION of the PROTECTION LEVELS			RISK for		
		Property & content	Occupants	Activities	Property & content	Occupants	Activities	Property & content	Occupants	Activities	Property & content	Occupants	Activities
Floor Number	**Compartment**	**P**	**P1**	**P2**	**A**	**A1**	**A2**	**D**	**D1**	**D2**	**R**	**R1**	**R2**
R+7	Technical Room	1,59	3,51	1,01	1,39	1,29	1,35	1,53	2,53	0,96	0,74	1,07	0,78
	Technical Room + Small Room	0,42	3,19	0,27	1,50	1,40	1,45	2,02	3,39	1,29	0,14	0,67	0,14
R+6	Double Bedroom	0,34	2,85	0,26	1,47	1,37	1,45	1,64	2,16	1,05	0,14	0,96	0,17
	Single Bedroom	0,34	2,87	0,26	1,48	1,38	1,45	1,64	2,16	1,05	0,14	0,96	0,17
	Waste Room	0,17	2,79	0,11	1,50	1,40	1,45	1,82	2,39	1,16	0,06	0,83	0,06
R+5	Middle care	0,33	2,59	0,25	1,47	1,37	1,45	1,64	2,16	1,05	0,14	0,87	0,17
R+4	Medical Office	0,29	2,42	0,17	1,60	1,50	1,55	1,82	2,39	1,16	0,10	0,67	0,10
R+3	Dirt Laboratory	0,29	2,42	0,17	1,60	1,50	1,55	1,82	2,39	1,16	0,10	0,67	0,10
	Clean Laboratory	0,37	2,29	0,23	1,60	1,50	1,55	1,82	2,39	1,16	0,13	0,64	0,13
R+2	Head nurse room	0,68	4,78	0,43	1,50	1,40	1,45	1,92	3,72	1,23	0,24	0,92	0,24
	Operating Room	0,30	1,56	0,19	1,60	1,50	1,55	1,82	3,54	1,16	0,10	0,29	0,11
R+1	Dirty Laundry Unit	0,25	2,33	0,15	1,50	1,40	1,45	1,82	2,39	1,16	0,09	0,70	0,09
	Clean Laundry Unit	0,14	1,65	0,09	1,50	1,40	1,45	1,82	3,54	1,16	0,05	0,33	0,05
R0	Radiologie-Osseaux4	0,18	1,07	0,11	1,30	1,30	1,25	2,02	3,23	1,29	0,07	0,26	0,07
R-1	Pharmacy + Cold Storage	0,23	2,00	0,17	1,60	1,50	1,55	1,92	2,52	1,23	0,07	0,53	0,09
	Pharmacy + Archives	0,30	2,84	0,19	1,50	1,40	1,45	1,92	2,52	1,23	0,10	0,81	0,11
Legend			Slight risk			Medium risk				High risk			

Table 6. FRAME method results for the G Bloc of the Clinique Sainte Elisabeth

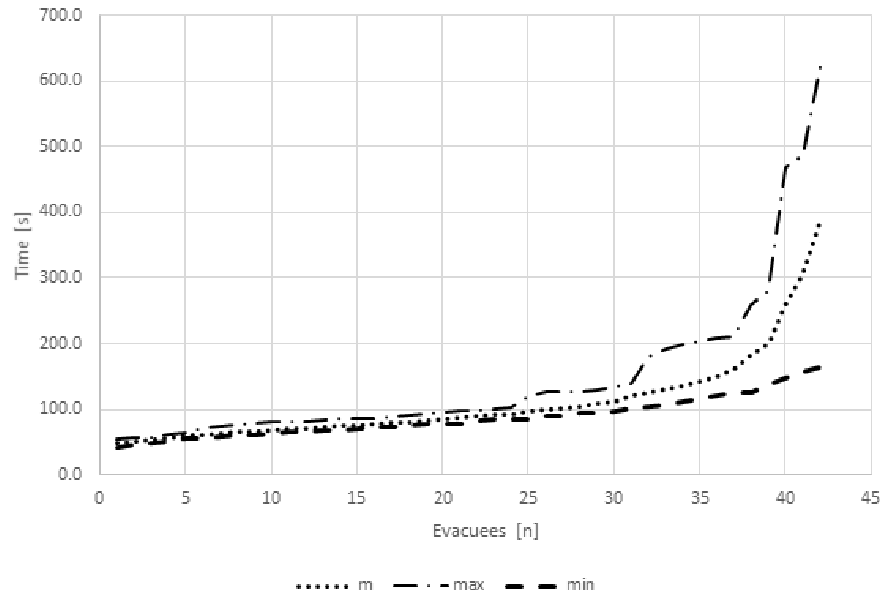

Figure 3. Evacuation curve for scenario 1 (m is the mean evacuation curve, max is the maximum evacuation curve and min is the minimum evacuation curve)

due to the fact that the evacuation of dependent and highly-dependent patients is delayed due to the preparation times required and the waiting for someone to assist them before starting to evacuate. Furthermore, when considering only dependent patients, there is a slight increase of the total evacuation time, while when considering a mix of dependent and highly-dependent patients, the increase of total evacuation time is extremely higher. This is due to the fact that (1) the time required to prepare highly-dependent patients is higher than the time required to prepare dependent patients and, (2) when evacuating a highly-dependent patient, the group (nurses + the patient) evolves at a reduced velocity comparing to the case when they assist on the evacuation of a dependent patient.

4.2.3. Scenario 3 The results from the scenario 3, compared in Figure 5, show that there is an increase in total evacuation time when considering a lower number of attendants. Indeed, when considering 6 EG (12 attendants) the total evacuation time is about 35 minutes, while when only 4 EG (8 attendants) are present, the total evacuation time increase to about 48 minutes. If we continue to reduce the number of emergency groups (e.g. evacuation during the night), a safe evacuation of the non-ambulant patients will not necessarily be guaranteed, since the total evacuation times will reach extremely high values.

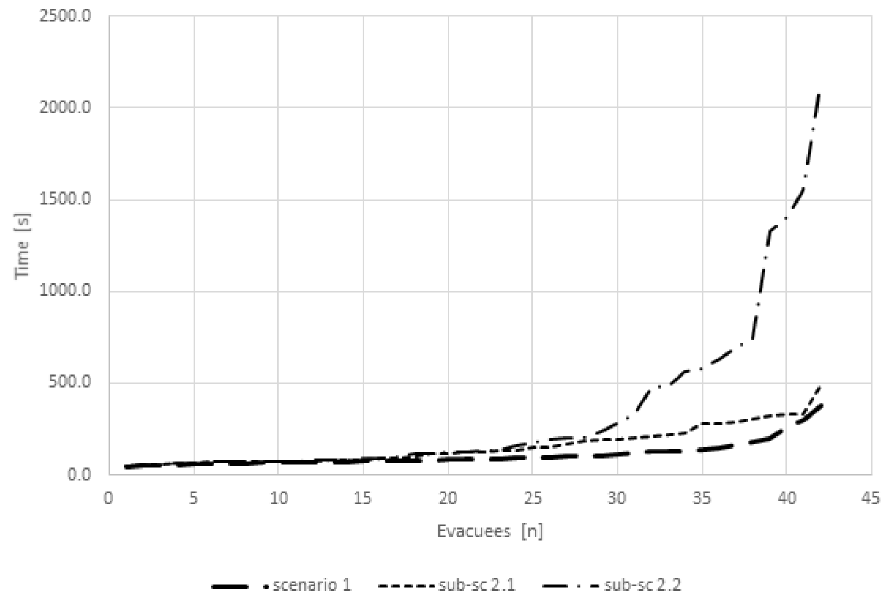

Figure 4. Comparison of the mean evacuation curves for scenario 1 and 2

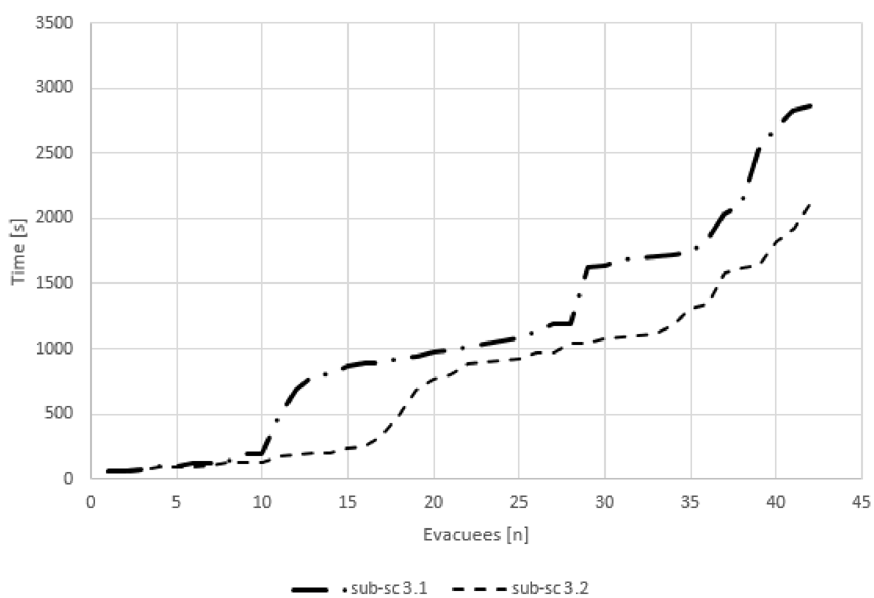

Figure 5. comparison of evacuation curves for scenario 3

5. CONCLUSIONS

The main objectives of this paper were: (1) the simulation of prescript assisted evacuation using and agent based model, i.e. Pathfinder2016; (2) the evaluation of the effect of different numbers and categories of people with reduced mobility on the evacuation process; and, (3) the study of the impact of staff to patient's ratio on the evacuation process.

The analysis of the results showed that (1) conducting an assisted evacuation takes a higher time than an evacuation involving ambulant patients only (2) the number of non-ambulant patients in the event of a fire should be designed to be as few as possible. This may be achieved by establishing a number of protected areas within the floors. Restricting the number of patients within each protected area will be of benefit in an evacuation in terms of fewer patients requiring to be moved away from the fire and reducing the total evacuation time needed; (3) the type of non-ambulant patients involved on the evacuation process influence the total evacuation time. Indeed, evacuating highly-dependent patients lead to a higher total evacuation time than evacuating dependent patients; and, (4) the presence of a large number of attendants leads to faster evacuation.

6. FUTURE WORK

This research highlighted a lack of data about preparation times, the number of attendants needed to assist the non-ambulant patients during the evacuation process and the walking speeds. Future data collection efforts are required to collect and analyze these variables. Further to this, more research is required to evaluate the effect of stress and fatigue perceived by the attendants during the repeated patient's collection. In addition, future works could investigate the impact of training of the attendants on the evacuation process. For example, by using virtual reality gaming techniques. Another important point to investigate is the integration of an explicit model to simulate assisted evacuations, such as the model developed by Hunt [10], into the evacuation models. Finally, future research could focus on the coupling of this analysis with the study of the possible effect of the fire on the evacuating population, e.g., the presence of the fire and smoke affects the peoples' behaviors, and there would be the need to simulate this impact on the evacuation process.

7. ACKNOWLEDGEMENT

The authors would thank the hospital “Clinique Sainte Elisabeth” managers for the material provided to conduct this study. The authors would also thank the staff for their helpfulness during the visit to the hospital.

REFERENCES

[1] Centre fédéral de connaissances pour la civile Sécurité. *Statistiques 2013 Des Services D'incendie Belges*. Techreport. 2013.

[2] D. Kuligowski; R.D. Peacock; B.L. Hoskins. *Technical Note 1680:A Review of Building Evacuation Models (2nd Edition)*. Techreport. NIST, Gaithersburg, USA. 2010.

[3] Santos; B.E. Aguirre. "A Critical Review of Emergency Evacuation Simulation Models." In *Proceeding of the NIST Workshop on Building Occupant Movement during Fire Emergencies*, 25–50. NIST, Gaithersburg, USA. Oct. 6AD.

[4] J.E Castle. *Guidelines for Assessing Pedestrian Evacuation Software Applications*. Edited by Centre for Advanced Spatial Analysis. University College London, London. 2007.

[5] M.V Gwynne; E.R. Galea; M. Owen; P.J. Lawrence; L. Fillipidis. "Review of Modelling Methodologies Used in the Simulation of Evacuation." *J. Build. Environ., 34*. 1999.

[6] M.V Gwynne; D. Kuligowski. "Application Modes of Egress Simulation." In *Proceeding of Pedestrian and Evacuation Dynamics*, 397–409. Wuppertal, Germany. 2008.

[7] M. Levin. "EXITT- A Simulation Model of Occupant Decisions and Actions in Residential Fires." In *Proceedings of the 2nd International Symposium on Fire Safety Science*. Tokyo, Japan. 1989.

[8] Yuya Christensen Keith; Sasaki. "Agent-Based Emergency Evacuation Simulation with Individuals with Disabilities in the Population." *Journal of Artificial Societies and Social Simulation* 11 (3): 9. 2008. http://jasss.soc.surrey.ac.uk/11/3/9.html.

[9] Parke; S. Gwynne; E. Galea; P. Lawrence. "Validating the buildingEXODUS Evacuation Model Using Data from an Unannounced Trial Evacuation." In *Proceedings of 2nd International Pedestrian and Evacuation Dynamics Conference*. London, UK. 2003.

[10] A. Hunt. "Simulating Hospital Evacuation." Phdthesis, University of Greenwich. 2016.

[11] W. Johnson. *Using Computer Simulations to Support a Risk-Based Approach for Hospital Evacuation*. Glasgow Accident Analysis Group, Department of Computing Science, University of Glasgow, Glasgow, UK. 2006.

[12] Uehara; K. Tomomatsu. "Evacuation Simulation System Considering Evacuee Profiles and Spatial Characteristics." In *Proceedings of the 7th International Symposium of Safety Science*, 963–974. 2001.

[13] Cuesta; O. Abreu; D. Alvear. "Evacuation Modeling Trends." Springer. 2016.

[14] Thunderhead. *Pathfinder 2016, Technical Reference*. 2016.

[15] T. Korhonen; S. Hostikka; Heliövaara; H. S Ehtamo; K. Matikainen. "FDS+Evac: Evacuation Module for Fire Dynamics Simulator." In *Interflam2007: 11th International Conference on Fire Science and Engineering*. London, UK. 2007.

[16] STEPS - Simulation Group. *STEPS (Simulation of Transient Evacuation and Pedestrian Movements) User Manual*. Edited by Mott MacDonald. Croydon, UK. 2011.

[17] Golmohamamdi; D. Shimshak. "Estimation of the Evacuation Time in an Emergency Situation in Hospitals." *Computer and Industrial Engineering*, 1256–1267. 2001.

[18] Alonso. *Egress Modelling in Health Care Occupancies*. The Fire Protection Research Foundation, Technical Notes, USA. 7AD.

[19] Ursetta; A. D'Orazio; L. Grossi; G. Carbotti; S. Casentini; L. Poggi. *Egress from a Hospital Ward: A Case Study*. FEMTC2014: Fire and Evacuation Modeling Technical Conference 2014. 2014. http://www.thunderheadeng.com/2014/10/femtc2014_d2-b-3_carbotti/.

[20] P.M. Adams; E.R. Galea. "An Experimental Evaluation of Movement Devices Used to Assist People with Reduced Mobility in High-Rise Building Evacuations." In *Pedestrian and Evacuation Dynamics 2010, 5th International Conference*, edited by E.D.; Averill, J.D. Peacock R.D.; Kuligowski, 129–138. Springer, New York, NY. 3AD.

[21] A. Hunt; E.R. Galea; P. Lawrence. "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 (4). Wiley-Blackwell: 407–429. Dec. 2013. doi:10.1002/fam.2215.

[22] John J Fruin. *Pedestrian Planning and Design*. Book; Book/Illustrated. Revised ed. Mobile, AL : Elevator World. 1987. Based on the author's thesis, originally presented at the Polytechnic Institute of Brooklyn under the title: Designing for pedestrians.

[23] International Maritime Organization, editor. *MSC Circ. 1248, Interim Guidelines for Evacuation Analyses for New and Existing Passenger Ships*. 2002.

[24] De Smet. "F.R.A.M.E: Fire Risk Assessment Method for Engineering." Sep. 2016. Accessed September 19. http://www.framemethod.net/indexen.html.

[25] De Smet. "F.R.A.M.E Calculation Report: Düsseldorf Airport." Sep. 2016. Accessed September 19. http://www.framemethod.net/indexen_15.html.

[26] De Smet. "F.R.A.M.E Calculation Report: Sofa Super Store Fire." Sep. 2016. Accessed September 19. http://www.framemethod.net/indexen_23.html.

[27] De Smet. "Example: Historic Building: 13-15 Century Monastery Used as Museum and Cultural Centre." Sep. 2016. Accessed September 19. http://www.framemethod.net/indexen_20.html.

[28] Project FiRE-TECH. "Fire Risk Evaluation to European Cultural Heritage European Study into the Fire Risk to European Cultural Heritage:WG6: Fire Risk Assessment Methods Draft Final Report." http://www.framemethod.net/indexen_html_files/wg6finalreport.pdf.

[29] De Smet. "F.R.A.M.E Calculation Report: Kanunnick Triest Te Melle." http://www.framemethod.net/indexnl_html_files/Brand%20in%20Zorgcentrum%20Kanunnik%20Triest%20te%20Melle.pdf.

[30] Rahouti; S. Datoussaïd. "Prédiction Du Risque Incendie En Milieu Hospitalier." In *GISEH16:La 8ème Conférence Francophone En Gestion et Ingénierie Des Systèmes Hospitaliers*. 2016.

[31] T. Korhonen; S. Hostikka. *Fire Dynamics Simulator with Evacuation – FDS+Evac, Version 2.5.0 – Technical Reference and User's Guide*. VTT, Helsinki, Finland. 2009.

[32] Nelson, and F. Mowrer. "Emergency Movement." In *SFPE Handbook of Fire Protection Engineering, Third Ed.*, edited by P. DiNenno. Quincy, MA. 2002.

[33] Gwynne; E.R. Galea; J. Parke; J Hickson. "The Collection and Analysis of Pre-Evacuation Time Data Collected from Evacuation Trials and Their Application to Evacuation Modeling." *Fire Technology*, number 2,39: 179–195. 2003.

[34] Gwynne; E.R. Galea; J. Parke; J Hickson. "The Collection of Pre-Evacuation Times from Evacuation Trials Involving Hospital Outpatient Facility, in Evans DD." In *Proceedings of the 7th International Symposium Fire Safety Science*, 877–888. IAFSS. 2002.

[35] E. Boyce; T.J. Shields; G.W.H. Silcock. "Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People Moving Horizontally and on an Incline." *Fire Technology*, number 35: 51–67. 1999.

[36] Walts; J. Stanford; P. Weydeck; J. Lukat; C. Larsen; G. Benigni; C. Grady; C. Gallaher. *Hospital Evacuation Toolkit*. Florida Department of Health. 2011.