FIRE SAFETY IN HOSPITAL BUILDINGS, with PERFORMANCE-BASED ANALYSIS

Nuno Coelho, António Correia, Susana Meneses

Coimbra Institute of Engineering – Polytechnic Institute of Coimbra, SUScita
Rua Pedro Nunes, Quinta da Nora
3030-199 Coimbra, Portugal
e-mail: antonio.correia@isec.pt

Nuno Correia

Department of Architecture – Faculty of Sciences and Technology of the University of Coimbra
Rua Colégio Novo
3000-143 Coimbra, Portugal
e-mail: ncorreia@darq.uc.pt

ABSTRACT

The risk of fire in an Hospital building is a topic of extreme importance for the safety of the population in general, and for the safeguarding of the occupants and equipment in that building. The publication of Fire Safety Regulations aim to improve the conditions for preparing buildings in the event of a fire. In this sense, it is important to analyze the fire safety conditions in existing buildings, so that safety is not only verified in new buildings. Particularly, in Hospital buildings, special care must be taken to safeguard them, mainly due to the difficulty in evacuating bedridden people and people with limited mobility needing medical assistance, also taking into account that, since the initial construction, buildings may undergo changes to improve their safety along the time.

In this paper, the subject of the fire safety of hospital buildings is addressed, with a particular study of a private clinic with inpatient and external consultations, where the evacuation plan was analyzed and articulated with the numerical modelling of the fire propagation, as well as with the modelling of the evacuation of the building, to assess whether the security measures implemented are adequate to safeguard the lives and property of the building under study. The case study is an existing clinic in the city of Coimbra, in Portugal. In the building, a survey was made of all potential hazards influencing the fire risk. Different fire scenarios were considered with the focus on the evacuation of people in beds, in which the assistance of auxiliary staff in needed.

The main objective of the study is to evaluate whether the patients in this hospital are safe, and to test the evacuation plan, in such a way to attempt to improve it. Moreover, a special attention will be paid to the smoke evacuation system, to improve the visibility during evacuation.

INTRODUCTION

Current legislation prescribes the performance of fire drills with a certain frequency. There are buildings in which, due to their characteristics, performing drills may imply the suspension of services, as the level of difficulty of doing them, for example in health units with users with reduced mobility, including bedridden, will be very high.

On one hand, it is useful to validate the regulatory requirements of conditions and times of evacuation of people through numerical modeling of fire and evacuation, and on the other hand, the criteria indicated in the Emergency Plans can be tested, both during the elaboration phase, as well as during the exploration phase of the buildings.

It is, therefore, the objective of this work to analyse Fire Safety in a Hospital Unit in Coimbra, with Performance-Based Analysis, concerning the egress and the propagation of smoke within the building. Special attention will be paid to the smoke evacuation system of the building, to improve it. The methodology to be used is the three-dimensional modeling of the building under study, starting from Autocad files, thus creating the 3D Revit model of the building. This 3D model is then exported to the Pyrosim software, where after defining the boundary conditions, with special detail on the floors, walls and ceiling covering materials, the simulation of fire propagation is performed. After this fire modeling, the Pathfinder software is used to, simultaneously with the fire simulation, program the building's evacuation protocol and verify the operation of the entire process. In this type of buildings, given the existence of bedridden people and people with limited mobility, an adequate security organization becomes essential, where auxiliary staff, medical and nursing staff, as well as eventually the intervention of firefighters, play a crucial role (Coelho, 2021).

CASE STUDY AND NUMERICAL MODELLING

Hospital da Luz Private Clinic in Coimbra

Hospital da Luz Coimbra is a reference for excellence in healthcare in Portugal. It provides outpatient services in several specialties, emergencies, medical examinations, as well as surgeries and hospitalizations. In addition to the University of Coimbra Hospitals, it is the most important health unit in the District of Coimbra. Figure 1 illustrates a side facade of the building under study. Figure 2 shows the 3D model of the building in REVIT (Coelho, 2021).

Figure 1: Illustration of a lateral facade of the Hospital da Luz Private Clinic

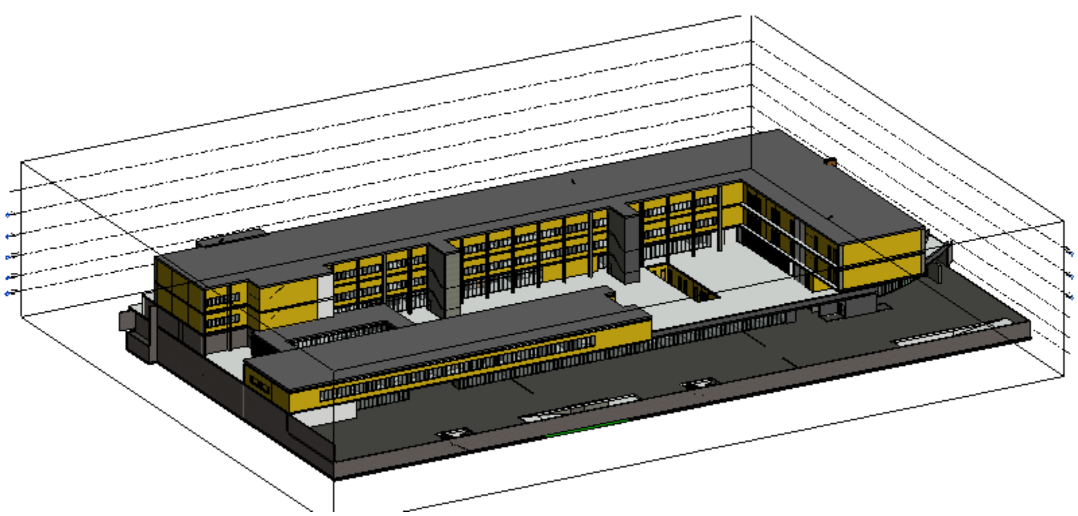


Figure 2: View of the 3D model of the building in REVIT.

Numerical modelling with Pyrosim and Pathfinder

As the name implies the Fire Dynamic Simulator (FDS) is a Computational Fluid Dynamics (CFD). This software, along with Smokeview, is the product of an international collaborative effort between the National Institute of Standards and Technology of the United States of America (NIST) and the Technical Research Center of Finland (VTT).

The software calculates and simulates the evolution of the fire, that is, the propagation of flames and smoke. The calculation is done using the Finite Element Method, using the Navier-Strokes equations. These are equations that allow the accurately modelling of a whole set of phenomena in single-phase turbulent or laminar incompressible flows, for compressible flows of all velocities and even multi-phase flows.

Smokeview is a result viewer that allows you to observe the simulation results. Through it, we can observe not only the development of the fire (propagation of flames and release of smoke) but also visualize the results chosen on the platform, such as: Temperature; Heat Release Rate; Visibility; Air speed, amongst others. Like the FDS, Smokeview is also a product of NIST and VTT.

Pathfinder is also a product of Thunderhead Engineering. It is then used to simulate outgoing human movement. It provides a graphical user interface for model design and simulation execution, as well as 2D and 3D visualization tools for analyzing results (Coelho, 2021).

Fire Scenarios

In this work, two fire scenarios and corresponding evacuations were studied. The scenarios consider ignition points in internment and external consultation areas. As it will be seen further on, the alternatives aimed to optimize ventilation and smoke removal in order to reduce the evacuation times of the sectors under study, as well as the danger to the occupants. This chapter presents the places where fires break out and the respective sectors to be evacuated. In this study, two scenarios will be presented: one in the inpatient area, and the other in the outpatient area. For both scenarios, two situations were considered: one with the actual smoke-removing systems of the building, and another with the proposed smoke-removing systems with higher smoke-removing powers. These proposals for new systems aim to control the levels of CO concentration to values below the limits susceptible to cause harm to human beings. To increase the performance on the evacuation of occupants, it was considered the aid of some firefighters on the evacuation.

Important to mention that the evacuation times were considered according to Hunt (Hunt, A., 2013).

Scenario A

Fire scenario A was considered on the 2nd floor of the internment. In this case the location of the fire source is in a room in the middle of the corridor. Figure 3 shows the location of the ignition point.

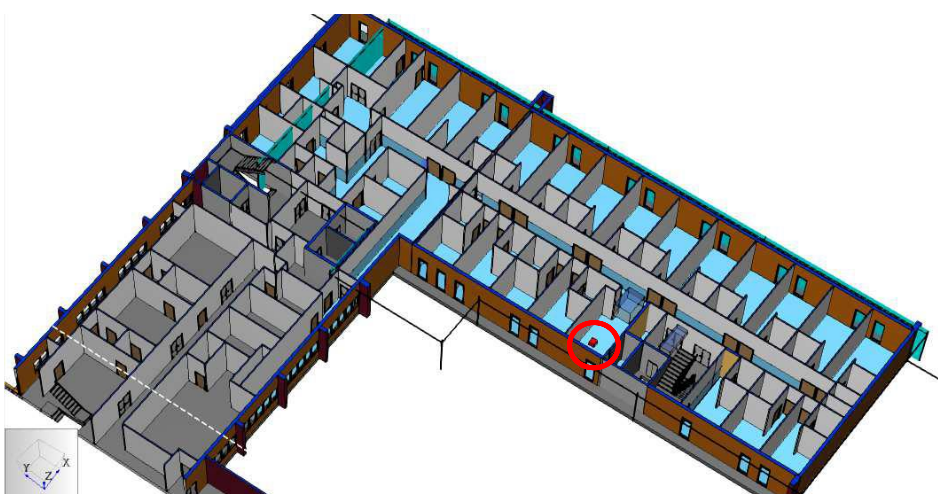


Figure 3: Location of the ignition point for scenario A

The following tables show the definition of the existing and proposed fire extraction systems for fire scenario A. In this case, an increase of power to the existing fans is proposed.

Clinic Ventilation System

Table 1: Summary table with insufflation and extraction flow rates existing in the building

Place	Number Fans Extraction	Extraction Flow (m3/s)	Total Extraction Flow (m3/s)	Number Fans Insufflation	Insufflation Flow (m3/s)	Total Insuflation Flow (m3/s)
Main Corridor	1	3	3	3	0,9; 1; 1,5	3,4

Proposed Ventilation

Table 2: Summary table with proposed insufflation and extraction flow rates

Place	Number Fans Extraction	Extraction Flow (m3/s)	Total Extraction Flow (m3/s)	Number Fans Insufflation	Insufflation Flow (m3/s)	Total Insuflation Flow (m3/s)
Main Corridor	1	6	6	3	2,0; 2,5; 2,5	7,0

Scenario B

Fire scenario B was considered on the 2nd floor, in outpatient consultations. In this case, the location of the fire source is at the reception, next to the waiting room, in the main lobby. Figure 4 shows the location of the ignition point.

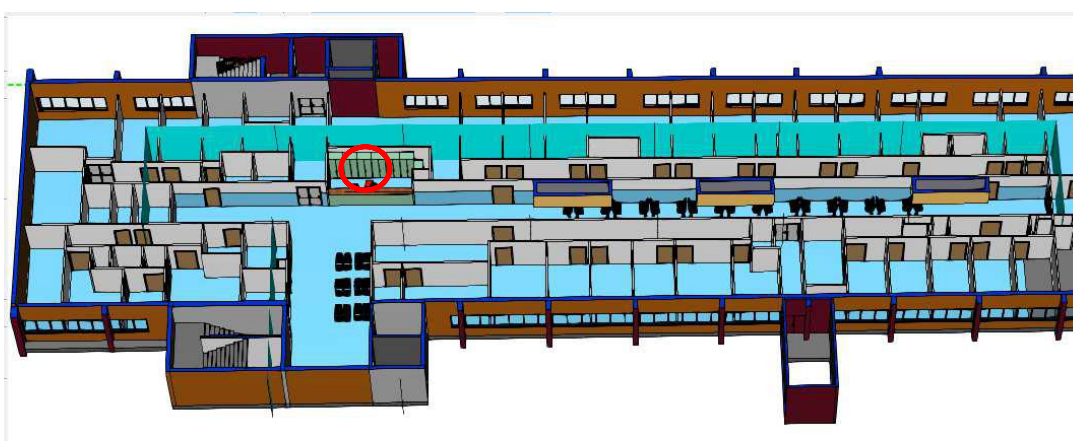


Figure 4: Location of the ignition point for scenario B

The following tables show the definition of the existing and proposed fire extraction systems for the fire scenario B. In this case, the proposal comprises an increase on the number of fans, from 3 to 4, maintaining the power, but increasing the total flow.

Clinic Ventilation System

Table 3: Summary table with insufflation and extraction flow rates indicated installed in the building

Place	Number Fans Extraction	Extraction Flow (m3/s)	Total Extraction Flow (m3/s)	Number Fans insufflation	Insufflation Flow (m3/s)	Total Insuflation Flow (m3/s)
Main Corridor	3	4; 4; 4	12	3	4; 4; 4	12
Corridor	-	-		-	-	

Proposed Ventilation

Table 4: Summary table with proposed insufflation and extraction flow rates

Place	Number Fans Extraction	Extraction Flow (m3/s)	Total Extraction Flow (m3/s)	Number Fans insufflation	Insufflation Flow (m3/s)	Total Insuflation Flow (m3/s)
Main Corridor	3	4; 4; 4	16	4	4; 4; 4;4	16
Corridor	1	4		-	-	

RESULTS

Scenario A

Table 5 shows the number of occupants per compartment. It is important to note that the entry of each element to aid evacuation is counted as an occupant. Given the length of time it takes to evacuate bedridden occupants compared to the evacuation times of autonomous occupants, only the compartments where bedridden occupants are situated were considered.

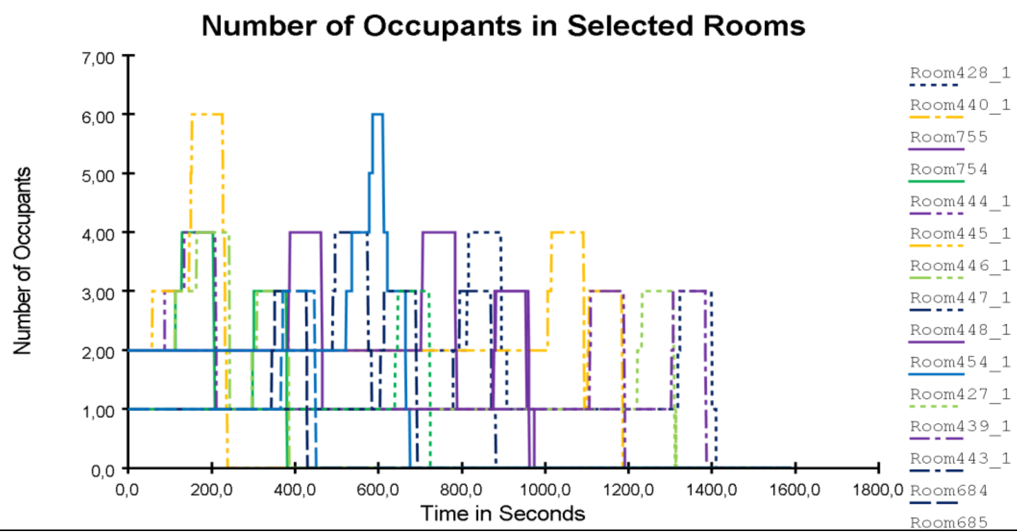
Table 5: Number of occupants in the compartments - Comparative Graphs

Compartment:

- Double inpatient rooms – 2.138; 2.140; 2.142; 2.144; 2.146; 2.148; 2.150; 2.152; 2.154; 2.156
- Individual inpatient rooms – 2.160; 2.162; 2.164; 2.170; 2.174; 2.178

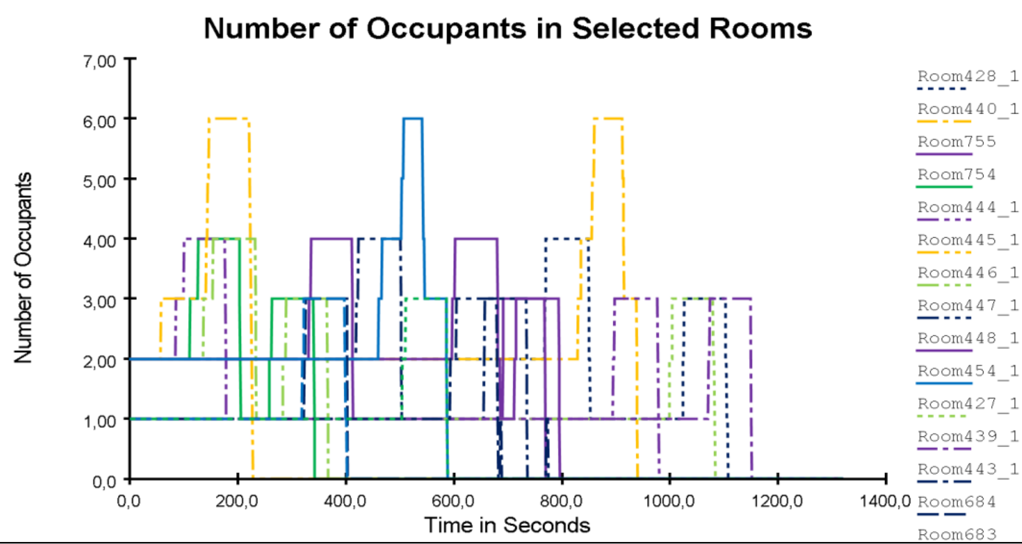
Occupants at start: 26 bedridden users (two per double room and one bedridden occupant in each single room); 10 medical staff; 10 additional staff (may be firefighters, arriving 8 minutes after the alarm).
Occupants at the end: 0

Building Ventilation System



Evacuation of spaces occur in seconds: 1444

Proposed ventilation system



Evacuation of spaces occur in seconds: 1160

From the analysis of the graphs, it can be seen that the evacuation times of the simulation of the proposed smoke extraction system are considerably lower than the simulation with the building's smoke extraction system.

Description of the evacuation (scenario A with proposed smoke extraction system)

At 60s the evacuation alarm is given. The smoke extraction system starts and opens the skylight in the waiting room. The evacuation of bedridden users begins. Comparing each of the parameters with those of the building's smoke removal system, it can be seen that in this simulation: Visibility is better

with the lowest value of about 5.40m; Temperature: the maximum value is lower; Oxygen Concentration is similar and Carbon Monoxide Concentration is lower, about half in the Corridor.
At 230s, the first bedridden occupants arrive at the Concentration Zone in the Refuge Sector. Visibility continues to increase, with minimum visibility being between 6 and 7 m. The temperature does not increase in the corridor and the concentration of Carbon Monoxide is maintained.
At 480s the firefighters arrive and begin aiding the evacuation operations to the outside of the bedridden 0ccupants. There are 10 bedridden occupants in the Concentration Zone. In part of the corridor, visibility is above 18m with a minimum of about 6.5m. The maximum value of the concentration of Carbon Monoxide is in the ceiling next to the fire source and at about 0.6%.
At 550s, firefighters begin removing bedridden occupants. In part of the corridor, visibility is greater than 18m, with a minimum value of about 6.5m. There are 15 bedridden occupants to be removed from the rooms.

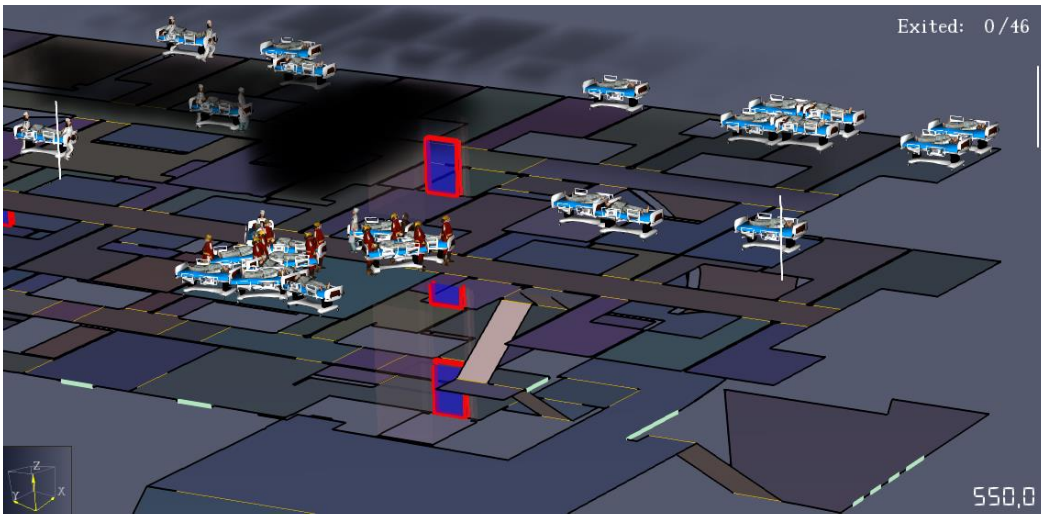


Figure 5: Evacuation simulation at 550 s

At 1160s the last bedridden occupant is removed from the 2nd floor. In the simulation with the building's ventilation system this moment occurred at 1444s and 29 occupants had left.
Visibility is maximum in half of the corridor (matching with the very low CO concentration value) and around 9m in the remaining corridor. 28 occupants have already left.
At 1251s, the last bedridden occupant who was in the Concentration Zone is removed.

<u>Scenario B</u>

In this scenario, as well as for scenario A, a simulation was carried out with the existing ventilation system of the building, and also a proposal for more efficient smoke removal was presented in order to achieve a better evacuation time.
The number of occupants considered was 227. These occupants are distributed as follows: 217 in the sector under study (16 bedridden occupants, 201 Health Technicians and autonomous occupants with escorts), and 10 firefighters arriving after 8 minutes..
When the fire is confirmed, the alarm is given (60s), smoke extraction ventilation and emergency evacuation of sector A1 are started (according to the Clinic Emergency Plan).

Table 6 shows the number of occupants per compartment for scenario B. The graphs depict the evolution of number of occupants in each compartment, along the time. Both situations are represented: one with the building ventilation system and the other with the proposed ventilation system.

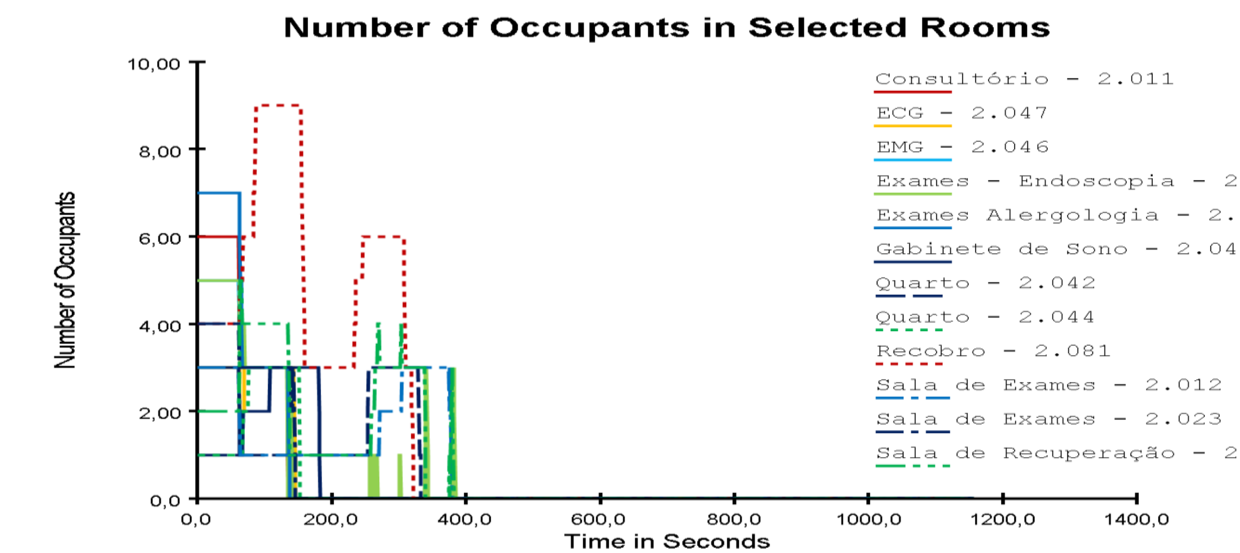
Table 6: Number of occupants in the compartments - Comparative Graphs

Compartments: Endoscopy Exams – 2016; Recovery Room – 2016; Exam Room – 2012; Office – 2012; Exam Room – 2,023; Allergology Exams – 2,039; Sleep Cabinet – 2,041; Room – 2,042; Room – 2,042; EMG - 2046; ECG - 2047; Recovery – 2,081;

Occupants at the beginning: 16 bedridden occupants; 201 Occupants (Health Technicians and Users); 10 firefighters

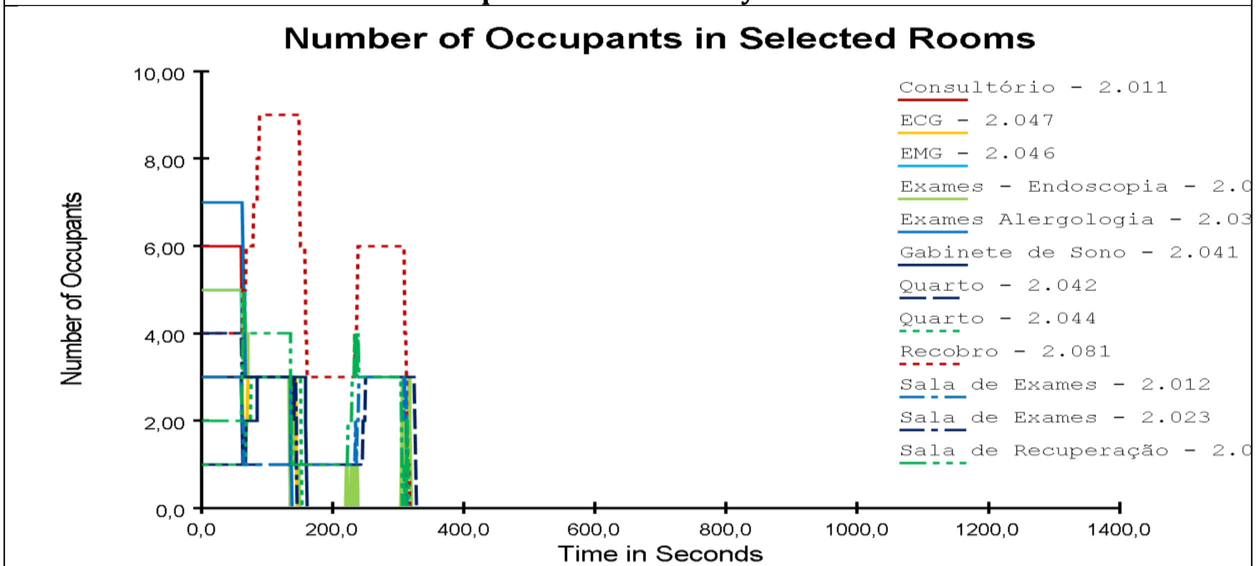
Occupants at the end: 0

Building Ventilation System



Last evacuation: Endoscopy Exams 2.019 - 383s

Proposed Ventilation System



Last evacuation: Room – 2.042 - 330s

The building ventilation graph shows that the last bedridden occupant leaves the room to be evacuated at 383s, while in the proposed ventilation graph it can be seen that the last bedridden occupant leaves the room at 330s.

Description of evacuation (scenario B with existing smoke extraction system)

At 20s, the Health Technician of the Ophthalmology Consultation Room 2.069 will find out what is going on up to the source of the fire. Smoke spreads to the hallways. Occupants who were in the corridors, go to the evacuation stairs of the North and South.

At 30s the Health Technician returns to the room and contacts the Security Post. The corridors are practically filled with smoke, as both visibility levels are reduced and CO levels are increasing.

At 60s, the occupants were checked to exit via the emergency stairs to the North and South. The evacuation alarm is given, the smoke extraction system starts and the skylights in the main corridor are opened. Visibility is practically null in the corridors. There are 12 occupants left. Health Technicians will evacuate bedridden occupants.

At 132s, the evacuation of bedridden occupants begins (4 practically simultaneously). Visibility in the main corridor is practically restored. In the other aisle, visibility is practically null. 63 occupants have already left. Occupants continue to exit via the North and South stairs.

At 193s, the first bedridden occupants arrive at the concentration area of sector B (the emergency plan indicates that it is in sector A2, however it is not marked on the plan, having been chosen to consider it in sector B). 135 occupants have already left. The fire took over the cabinets and temperature is around 400°C.

At 456s, the last bedridden user is removed from the sector to be evacuated. Visibility in the main aisle remains above 18 m, however in the other aisle visibility is less than 3m. A reduction in the concentration of Oxygen and an increase in the concentration of Carbon Monoxide can be seen. The concentration of Carbon Monoxide (Figure 6 – t=456s) reaches values above 0.2% in this area, which already causes symptoms in humans (headache after 10 minutes, collapse after 20 minutes and death after 45 minutes) (Marsar, 2009). 197 occupants have already left. The fire reaches temperatures above 500°. When leaving the service area. There are no more users in the sector.

At 480s the firefighters crew arrive. The last bedridden user evacuated from the floor enters the stretcher concentration area on the 1st floor. 199 occupants left. In the secondary corridor, the concentration of Carbon Monoxide continues to increase, as well as the temperature. The flame is crossing the corridor (Figure 7 – t=480s).

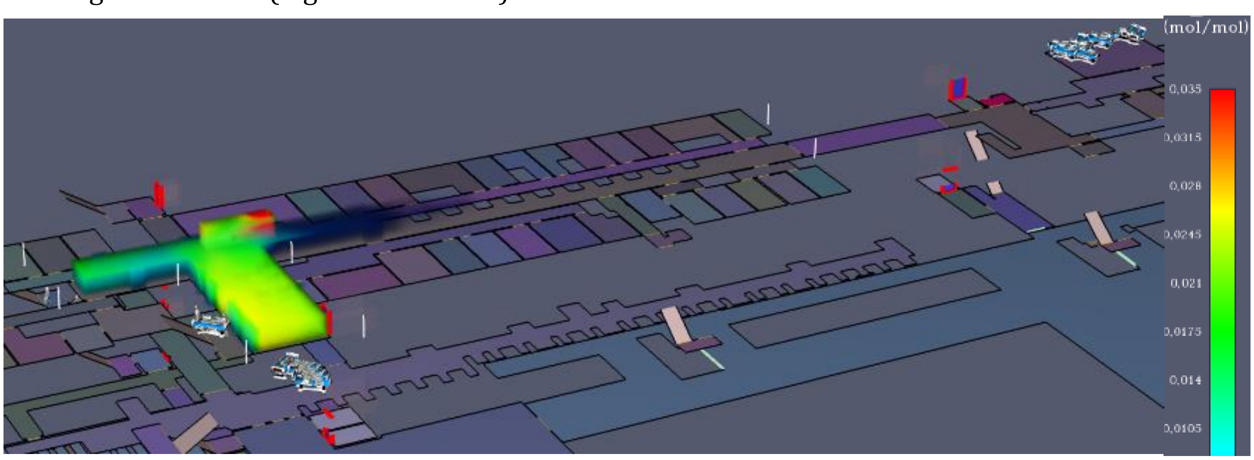


Figure 6 – Carbon Monoxide Volume Fraction (3D) – t=456s

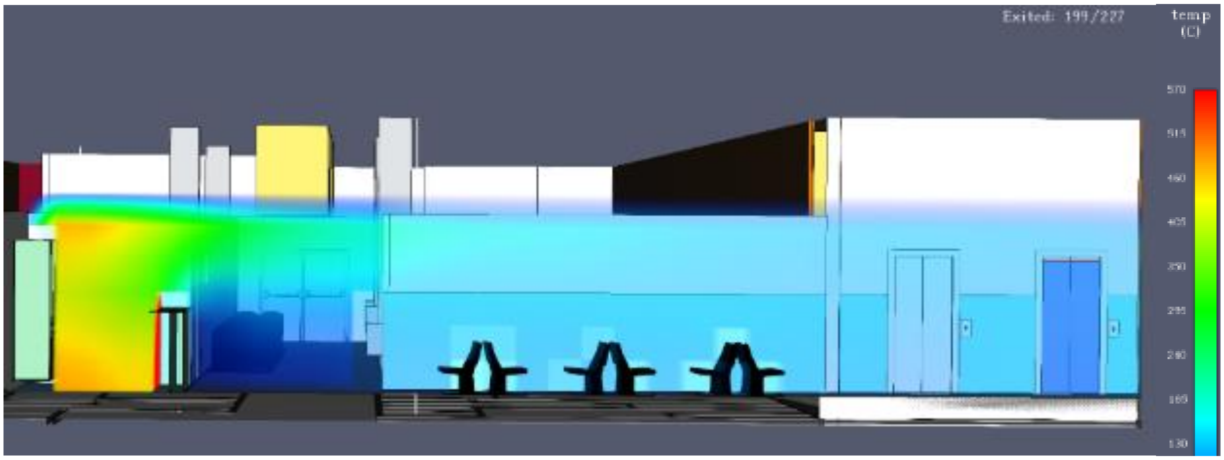


Figure 7 – Reception Temperature (3D) – t=480s

Figure 8: Evacuation of the Concentration Zone

At 588s the firefighters arrive at the concentration zone on floor 2 (Figure 8 – t=588s). At this instant 201 occupants left. The fire spread to the chairs in the waiting room, further raising the temperature and concentration of gases in that area.
At 670s, an elevator is used by firefighters in vertical evacuation. It is noticed that the chairs in the waiting room were consumed. At this time 202 occupants left.
At 1019s the last occupant is routed to the exit. 216 occupants left. The fire loses intensity as observed by the lowering of temperatures.

Synopsis

Table 7 shows the evacuation times of bedridden occupants to the outside of the building.
In this table, the times for scenario B with the existing ventilation system and with the alternative system are identical. The reason for these values has to do with the fact that in the two simulations the bedridden occupants are placed in the concentration area in a time shorter than the time of entry of the firefighters (480s) and therefore the two scenarios from that time on, are identical (evacuation of bedridden occupants and firefighters to the outside) (Coelho, 2021).

Table 7: Evacuation Times Bedridden Users and Firefighters

Scenario	Time required for Evacuation Occupants (s) *	Time required for Evacuation Occupants (min:s)*
A	1565	26:05
A - Proposal	1297	21:37
B	1019	16:59
B - Proposal	1019	16:59

(*) To the outside of the building

CONCLUSIONS

The evacuation of people in hospital buildings in a fire situation is in all situations very important. When it comes to hospital buildings where there are occupants who, due to their characteristics, need assistance, then the difficulty of evacuation increases greatly. The possibility of carrying out simulations in health units with real occupants is of great difficulty, as it is understood that it is not feasible in units that are in operation to carry out fire drills with occupants with real illness.

In scenarios A and B, alternatives were carried out in order to reduce the amount of smoke in the horizontal evacuation routes, so that shorter evacuation times were achieved. From the analysis of the graphs, it was noticed that the increase in ventilation caused better smoke removal and resulted in the intended reduction of evacuation times, mainly in scenario A. It was concluded that it is possible to optimize the ventilation systems, with the objective of reducing evacuation times due to the higher evacuation speeds of users, being important to compare the results of real fire evacuation drills, with the results of the computer simulations, to calibrate the virtual models, thus being able to explore the potential of the advantage of the "virtual" where it becomes difficult or impracticable to carry out real evacuation exercises as in areas of occupants with reduced mobility. The present study allowed to achieve the conclusion that an improvement of the ventilation system is effective in scenario A, and not so much in scenario B. Another important conclusion is that the firefighters aid in evacuation occupants in beds, may be of great importance to prevent them to be exposed to high levels of Carbon Monoxide.

ACKNOWLEDGEMENTS

The authors greatly acknowledge Thunderhead Engineering for the free assignment of Academic Licences of Pyrosim and Pathfinder, for students of the Superior School of Engineering of Coimbra, Polytechnic of Coimbra.

REFERENCES

Andersson, L. (1988), "Risker och brister vid utrymning. Brandingenjorslinjen", Lunds Tekniska Hogskola. Lund : Universitetsbiblioteket, pp. 13-27.

Coelho, L. (1997), "Modelação Matemática da Evacuação de Edifícios Sujeitos à Acção de um Incêndio". Volumes I e II ed. Porto. Porto : Departamento de Engenharia Civil da Faculdade de Engenharia da Universidade do Porto, 1997.

Coelho, N. (2021), "Segurança contra incêndios em Edifícios Hospitalares, com análise Baseada no Desempenho e por Abordagem Prescritiva", Tese de Mestrado, Departamento de Engenharia

Civil do Instituto Superior de Engenharia de Coimbra, Instituto Politécnico de Coimbra, https://www.academia.edu/67213352/Nuno_CoelhoDR0_1_

Dolvitsch, J., Ruschel, F. and Silva Filho, L., (2011). Avaliação da Utilização de Métodos Computacionais na Reconstituição de Incêndios em Edificações: Caso do Shopping Total em Porto Alegre. Rio Grande do Sul : Anais: I Congresso Ibero-Latino Americano sobre Segurança Contra Incêndio

Fechinha, P. (2018), "Segurança Contra Incêndios em edifícios de Centros Urbanos Antigos", Tese de Mestrado em Engenharia Civil, Especialidade em Construção Urbana, ISEC, Instituto Politécnico de Coimbra

Hunt, A., Galea, E., Laurence, P., (2013) "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,, https://doi.org/10.1002/fam.2215

Jahn, W., Rein, G. and Torero, J. (2011), "A posteriori modelling of the growth phase of Dalmarnock Fire Test One", Building and Environment. 2011, Vol. 46, pp. 1065-1073.

Kim, J. and Lilley, D. (2000), "Heat Release Rates of Burning Items in Fires." AIAA 2000-0722. Reno : 38th Aerospace Sciences Meeting & Exhibit

Lawson, J., Walton, W. and Twilley, W., (1984), "Fire Performance of Furnishings as Measured in the NBS Furniture Calorimeter", 1

MaGrattan, K. (2004), "Simulation of the Fires in WTC 1 and 2 - Federal Building and Fire Safety Investigation of the World Trade Center Disaster", NIST.

Marsar, Stephen, (2009) “Survivability Profiling: How long Can Victims Survive in a Fira? ", Fire Engineering.com

Moukalled, F., Mangani, L and Darwish, M. (2015), The Finite Volume Method in Computational Fluid Dynamics. s.l. : Springer, Vol. 113. ISBN 978-3-319-16874-6.

Torero, J., Jahn, W. and Rein, G. (2007), The Dalmarnock Fire Tests: Experiments and Modelling. Edimburgo : Universidade de Edimburgo, Vol. 11. ISBN 978-0-9557497-0-4.

Thunderhead Engineering. (2020), "Pyrosim User Manual" Thunderhead Engineering, Manhattan, USA

Thunderhead Engineering (2020), “Pathfinder – Technical reference”., Manhattan, USA

Wetterlund, I. and Goransson, U. (1988) "A Full Scale Fire Test Method for Free-Hanging Curtain and Drapery Textiles", ISBN 91-7848-130-9.

Wood, P. (1972) "The behaviour of people in Fires", s.l., Loughborough University of Technology