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Article

Guiding Evacuees to Improve Fire Building Evacuation Efficiency: Hazard and Congestion Models to Support Decision Making by a Context-Aware Recommender System

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Abstract: Fires in large buildings can have tragic consequences, including the loss of human lives. Despite the advancements in building construction and fire safety technologies, the unpredictable nature of fires, particularly in large buildings, remains an enormous challenge. Acknowledging the paramount importance of prioritising human safety, the academic community has been focusing consistently on enhancing the efficiency of building evacuation. While previous studies have integrated evacuation simulation models, aiding in aspects such as the design of evacuation routes and emergency signalling, modelling human behaviour during a fire emergency remains challenging due to cognitive complexities. Moreover, behavioural differences from country to country add another layer of complexity, hindering the creation of a universal behaviour model. Instead of centring on modelling the occupant behaviour, this paper proposes an innovative approach aimed at enhancing the occupants' behaviour predictability by providing real-time information to the occupants regarding the most suitable evacuation routes. The proposed models use a building's environmental conditions to generate contextual information, aiding in developing solutions to make the occupants' behaviour more predictable by providing them with real-time information on the most appropriate and efficient evacuation routes at each moment, guiding the occupants to safety during a fire emergency. The models were incorporated into a context-aware recommender system for testing purposes. The simulation results indicate that such a system, coupled with hazard and congestion models, positively influences the occupants' behaviour, fostering faster adaptation to the environmental conditions and ultimately enhancing the efficiency of building evacuations.

Keywords: fire building evacuation; human behaviour; Internet of Things; building evacuation efficiency; multi-agent recommender system; context-aware recommender system

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1. Introduction

Evacuating buildings during a fire is a sensitive issue for society, as it involves safeguarding human lives. Therefore, the research on fire building evacuation has witnessed significant developments in recent decades, focusing on modelling and simulating the movement and behaviour of a building's occupants.

The primary purpose of modelling human behaviour is to incorporate these models into the simulation models to understand the building evacuation phenomenon better and assist the architects and engineers in the building's design; however, as Gwynne [1] pointed out, the difficulties in simulating the occupants' cognitive processes in an emergency lead to a very limited representation of human behaviour in building evacuation models during a fire. Cordeiro [2] similarly stated that models that try to simulate people's behaviour during a building evacuation do so in a simplified way and are very dependent on the sensitivity and knowledge of those who use such a model.

Considering the difficulties mentioned above, this paper presents an evacuation solution based on a paradigm shift regarding the approach to the occupants' behaviour in a building during a fire emergency. In this paradigm shift, the focus is moved from trying to understand the occupants' behaviour for incorporating it into simulation models to helping the occupants behave more predictably by developing a system that can provide them with the real-time information they need to reach a safe place. Inducing a more predictable behaviour of the occupants during the evacuation also contributes to reducing the uncertainty typically associated with the evacuation of a building.

In the solution proposed here, providing real-time information to the occupants about the safest and most efficient evacuation routes includes the installation of IoT sensors in buildings so that it will be possible to know the environmental conditions of the various spaces that the occupants must move through.

Based on the studies by Coelho [3] and Predtechenskii and Milinski [4] and Standard PD 7974-6:2019 of the British Standards Institution [5], we developed contextual factor models to address the congestion of the evacuation routes, as well as the risk caused by fire, namely smoke, toxic and asphyxiating gases, and heat [6].

This article's main novelty and contribution reside in the development of models that use contextual information about the environmental conditions of buildings generated from the data obtained by IoT sensors to support decision making in guiding the occupants of a building during a fire. These models were incorporated into a context-based multi-agent recommendation system [6], and the test results suggest that if the occupants adapt their behaviour by following the system's recommendations, it will be possible to improve the efficiency of building evacuation during a fire.

As for the remainder of the article, Section 2 presents the research on fire evacuation of buildings. Section 3 presents the contextual factor models and the theoretical knowledge that supports them. Section 4 describes the testing of the developed models, and the simulation results are discussed in Section 5. Finally, in Section 6, conclusions and future work are presented.

2. Related Work

The study of the problems related to the evacuation of buildings in emergencies has drawn the attention of researchers over the past decades, with different approaches and motivations, which we can divide into three areas of research: (i) evacuation models, systems, and algorithms; (ii) study of occupant behaviour during the evacuation process; and (iii) guiding the occupants to a safe place in real time. The following subsections summarise the developments in these three areas based on the published literature reviews, surveys, and state-of-the-art papers.

2.1. Evacuation Models, Systems, and Algorithms

Most literature reviews focus on surveying evacuation models, systems, and algorithms. In their study, Gwynne, Galea, Owen, Lawrence, and Filippidis [7] analysed 22 evacuation models and considered three approaches. Optimisation models, in which the occupants are treated as a whole, do not consider an individual evacuee's behaviour. Simulation models intend to represent the behaviour and movement of the occupants during the evacuation process. Finally, risk assessment models seek to identify hazards and quantify the risk associated with the evacuation from a fire or other incidents. Another review, developed by Hamacher and Tjandra [8], investigates models and algorithms applicable to the building evacuation problem. The authors distinguish between microscopic and macroscopic evacuation models. The microscopic models are based on simulation and can model the evacuees' characteristics and the interactions among them that influence their movement. The macroscopic evacuation models are this paper's primary focus; those models do not consider individual behaviours during evacuation and use optimisation algorithms. To provide information that helps in choosing the most suitable model, Kuligowski and Peacock [9] present a comprehensive review of 30 building evacuation models. The authors classify the models according to several categories, such as the modelling method used and its purpose, the type of occupants' movement and behaviour, and the incorporation, or not, of fire data in the simulation. Also dividing the models into two types, macroscopic and microscopic, Dhamala [10] presents the building evacuation domain's state-of-the-art models, algorithms, applications, and implementations. The author highlights the advantages and disadvantages of the analysed models, referring to the difficulty in establishing consensus when comparing performances. Models based on optimal and approximate solutions, namely based on heuristics, are considered in the analysis.

2.2. Study of Occupants' Behaviour during the Evacuation Process

Much of the researchers' interest focused on studying occupant behaviour during the building evacuation. For Vorst [11], modelling an evacuation process in an emergency must consider the behaviour of the occupants, namely the negative impact resulting from the psychological state of the occupants. In their reviews, Kobes et al. [12] and Ronchi et al. [13] emphasise the importance of understanding human behaviour in the design and construction of buildings, considering that the occupants' behaviour interacts with the surroundings and with the implemented building safety measures. The authors highlight the importance of identifying the behavioural factors influencing the building evacuation process, the knowledge of the building's purpose, as well as the knowledge of it by its occupants.

Understanding or training and educating human behaviour in a building evacuation situation contributes to designing safer buildings and more effective building evacuation processes. However, training based on drills, seminars, videos, or presentations may not be the most appropriate way to acquire and retain knowledge [14]. So, researchers have been proposing, studying, and evaluating the use of innovative technologies such as Serious Games and Augmented Reality. In their systematic literature review, ref. [14] seek to understand the development and implementation of solutions based on Immersive Virtual Reality (IVR) Serious Games (SG) in building evacuation for training people and behavioural study. In their work, the authors identify 15 papers, based on which they propose a framework to support the development of IVR SG applications for use in building evacuation. Noting that Augmented Reality (AR) can contribute, with virtual content, to improving occupants' performance in building evacuation, Ruggiero [15] presents a review of the AR applications developed for building evacuation. The author identifies AR applications, their goals, the hardware involved, and the incidents and building types supported and concludes that AR applications help increase the realism of building evacuation training and provide building occupants with solutions that enhance their performance in building evacuation.

For Gwynne [1], modelling human behaviour in buildings under a fire emergency is very limited due to the difficulty of modelling the cognitive process during the emergency. According to Cordeiro [2], models that seek to simulate human behaviour tend to do so in a very simplified way and depend on the information the user provides to the model. In her study on the state of the art of modelling human behaviour in case of a fire, Cordeiro [2] concludes the following: (i) the behaviour of occupants varies from country to country due to the different characteristics of populations; (ii) the nature of the event and the difficulty in obtaining data in real situations has not allowed for more significant consolidation of knowledge; (iii) the use of Serious Games can help to enrich knowledge and improve the understanding of behaviour profiles; and (iv) there are no studies that allow quantifying the time associated with actions taken by occupants before deciding to leave the building.

2.3. Guiding the Building Occupants to a Safe Place in Real-Time

A third area of research refers to developing solutions to guide the building occupants to a safe place in real time.

In the literature review on Intelligent Evacuation Management Systems (IEMS), developed by Ibrahim et al. [16] and Bi et al. [17], the authors devote a section to solutions that suggest the most appropriate safe evacuation routes. The authors believe that for an IEMS to be successful, it must be able to suggest to the occupants the most appropriate directions and paths so that they can reach safety zones. For the authors, the main objectives are to reduce the evacuation time and avoid congestion and blockage of the routes. The authors also refer to five methods of notification of evacuation routes to occupants: through mobile apps, enlarged photos with indicative arrows, digital displays, intelligent lighting, and sound signalling. In their survey, Bi et al. [17] present state-of-the-art emergency evacuation and evacuation guidance research, focusing on algorithms and systems. The authors highlight the impacts of the Internet of Things (IoT) developments and information and communication technologies (ICT) in disaster mitigation and prevention. The authors identify two lines of research: evacuation guidance and emergency search and rescue, focusing their work on developments in the first of the above areas. The authors define evacuation guidance as the process of directing evacuees through safe zones with the help of algorithms or using pre-designed static evacuation plans based on the prediction and analysis of evacuees' behaviour models. Concerning evacuation systems, the authors report that they have accompanied the development of ICT from human experience-driven systems developed between the 1970s and 1990s, ranging from wireless sensor-based network systems to systems based on the cloud and mobile devices. The authors conduct an exhaustive survey concerning algorithms, differentiating between offline and online algorithms. Offline algorithms focus on optimising crowded space design and evaluating evacuation time. Online algorithms intend to provide safe evacuation routes to evacuees in real time, combining mathematical models or algorithms with sensors, communication, and computing devices. The authors also identify possible future lines of research, such as developing algorithms supported by artificial intelligence to improve evacuation path determination and resource allocation and the use of multi-agent systems technology to model and develop better cooperation strategies.

Due to its rapid development, the Internet of Things (IoT) can now provide smart buildings with devices to assist occupants during emergency evacuations. Along with the advancements in IoT, recent years have also witnessed a significant surge in research studies aimed at integrating AI (artificial intelligence) and ML (machine learning) techniques to detect fire incidents and determine the most efficient evacuation routes in real time within smart buildings. Fang et al. [18] present a review of the developments in fire evacuation systems in smart buildings, noting that combining IoT with 5G can contribute to better solutions capable of helping occupants leave a building safely. In their paper, ref. [18] present an IoT-aided building fire evacuation solution that integrates IoT, 5G, and BIM technologies, which they believe may improve the evacuation of the building in case of a fire more efficiently. Wehbe et al. [19] unveiled an intelligent evacuation guidance system based on Building Information Modelling (BIM) for smart buildings. This system can detect fires promptly, gather and scrutinise sensor-derived hazard data, and proficiently direct evacuees to exits using optimal paths. Incorporating IoT and smart technology, their system detects fires early while minimising false alarms. Zualkernan et al. [20] introduced an emergency evacuation system centred on the Internet of Things (IoT), designed to collect information about conditions inside a building during a fire crisis, aiming to direct evacuees to a safe place. Nguyen et al. [21] present an intelligent evacuation guidance system for large buildings that uses smart indicators to provide real-time information to evacuees during emergencies. The system is designed with multiple computation layers. It proposes a dynamic evacuation routing approach using the LCDT (Length–Capacity–Density–Trustiness) weighted graph model and partial view (PV) information, representing the hazard intensity and the crowd congestion information of a group of sections/floors in the building. An estimated congestion strategy is also proposed to improve the efficiency of the evacuation routes. Lee et al. [22] introduced a new paradigm in developing assistive technologies. Their approach employs IoT sensors embedded within buildings to gather data concerning hazardous indicators like smoke or fire and use machine learning algorithms to determine safe evacuation routes.

3. Guiding Occupants to Improve Building Evacuation Efficiency

As mentioned previously, researchers have focused on studying the behaviour of building occupants to incorporate it into building evacuation simulation models. Despite this effort, modelling human behaviour during a fire emergency is limited due to the complexity of modelling cognitive processes during an emergency [1]. Additionally, human behaviour during emergencies is influenced by various factors that are difficult to predict and can vary from country to country [2].

Considering the difficulties mentioned above, we present an approach that considers a paradigm shift in dealing with human behaviour during building evacuation. This paradigm shift resides in the fact that instead of focusing on the understanding and modelling of the occupants' behaviour in a building under fire, the proposed approach focuses on the development of a solution capable of providing real-time information on the most appropriate and efficient evacuation routes at any given time. In possession of this information, the evacuees tend to adopt a behaviour that is adequate to the building's environmental conditions, resulting from the fire outbreak. Saini et al. [23] proposed an intelligent evacuation system designed to guide evacuees effectively toward safer locations while reducing direct fire exposure. The system uses IoT to capture hazardous conditions within the building and track evacuee movements and an evacuation routing to compute efficient routes that steer evacuees towards exits based on building conditions and evacuees' information.

3.1. Building Evacuation Time

The Standard PD 7974-6:2019 [5] considers two fundamental concepts that must be considered in fire building evacuation: the time available for a safe evacuation (ASET—available safe escape time) and the time required for a safe escape (RSET—required safe escape time). Figure 1 presents the various types of times related to ASET and RSET.

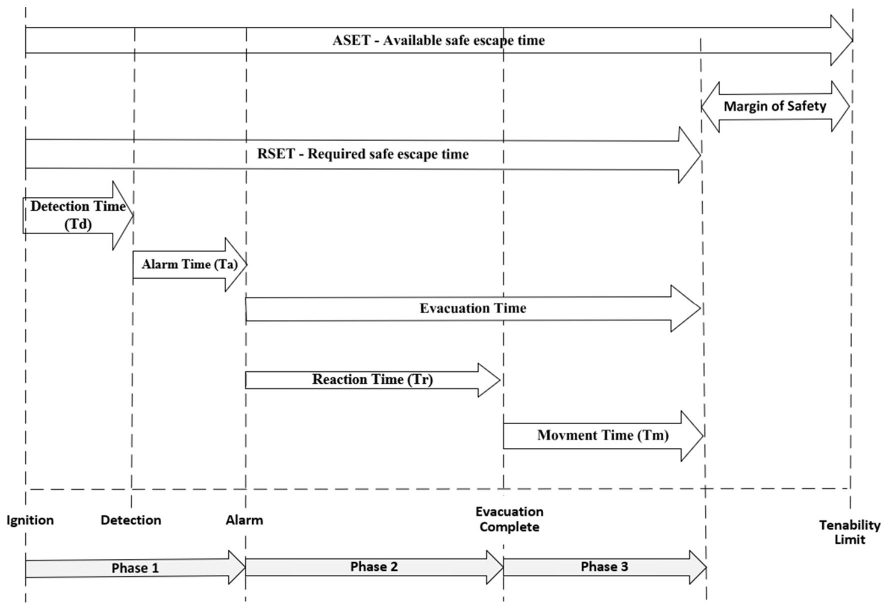


Figure 1. Simplified schematic of processes involved in safe escape time compared to available safe escape time, according to the Standard PD 7974-6:2019 specification in [5].

Thus, the evacuation of a building can be considered safe if the time available for it to occur safely is substantially longer than the time that the routes are not risky to the occupants, so:

$$\text{ASET} >> \text{RSET}. \quad (1)$$

From Figure 1, RSET may be written by the expression:

$$\text{RSET} = T_d + T_a + T_r + T_m \quad (2)$$

where

1. T_d is the time between the fire ignition and its detection by the fire detection system.
2. T_a is the time between the fire detection and the alarm sounding for evacuation.
3. T_r is the reaction time of the occupant to the alarm, which spans between the sounding of the fire alarm and the beginning of the occupant's movement to leave the building.
4. T_m is the movement or travel time that mediates between the moment an occupant starts moving to exit the building until he reaches a safe place.

As shown in Figure 1, the evacuation of a building in a fire emergency can be divided into three distinct phases.

Phase 1 corresponds to the period between the start of the fire and the building occupants becoming aware of it, being the sum of the detection time and the alarm time. Naturally, its duration depends on the type of building, the fire characteristics, the fire detection system, as well as the building's security procedures. Still, it does not depend on the characteristics of the occupants or their behaviour [2,3].

Phase 2 occurs between the moment the occupant becomes aware of the fire and when he starts moving to leave the building. Unlike phase one, the duration of this phase strongly depends on the occupants' behaviour and characteristics. However, it depends less on other factors, such as the type of building, the characteristics of the fire, and the security means installed [2,3].

Phase 3 corresponds to the time that an occupant takes to reach a safe place from when he decides to move out of the building. The duration of this phase depends on the occupants' behaviour, the building's characteristics, and the fire impact on the evacuation routes [2,3].

The solution presented here falls within the scope of phase 3, as its purpose is to guide the occupants to leave the building safely during their movement.

3.2. Fire Impact on the Fluidity of Building Evacuation Routes

When designing and constructing a building, emergency evacuation routes are designed so that, in the event of a fire emergency, building occupants can use them to exit the building safely. These evacuation routes are reflected in the building's emergency plan and construction by installing the respective emergency signage. The ontologies presented in [24,25] propose knowledge models that allow for a better understanding of the evacuation of buildings in case of fire. In [25], the author presents an ontological model to support the development of solutions and systems capable of guiding the occupants of a building on their way out of the building, i.e., during phase 3 of the previously identified evacuation process.

As a result of a fire outbreak, evacuation routes' availability and fluidity are reduced due to the fire's impact, leading to blockages and interruptions of these routes and degradation of the evacuation process. The impact on evacuation routes is the result of two types of factors. On the one hand, due to route congestion caused by the occupants' movement to exit the building and. on the other hand, the fire's hazard resulting from the combustion itself, smoke, toxic gases, and the increase in temperature inside the building, which lead to constraints on evacuation routes.

Thus, a fire impacts the building's environmental conditions, causing a change in the context in which the occupants are situated and the consequent change in the evacuation routes.

In the scope of this paper, context represents something that acts as a set of constraints that influence the behaviour of a system or user in the execution of a task [26]. Context is the information used to characterise the situation of an entity in an interaction, being the entity, a person, a place, or an object relevant to the interaction between a user and an application [27].

So, in the scope of this paper, context is defined as the information that, at each moment, allows the characterisation of the building's evacuation routes and the interaction with the building occupants. The ontological model developed by [25] considers that contextual information is constructed from the data obtained by the different IoT input devices installed in the building, be they IoT sensors of different types or fire detection systems. This construction process of contextual information characterising the building environment is shown in Figure 2, which is obtained from the ontology proposed by [25].

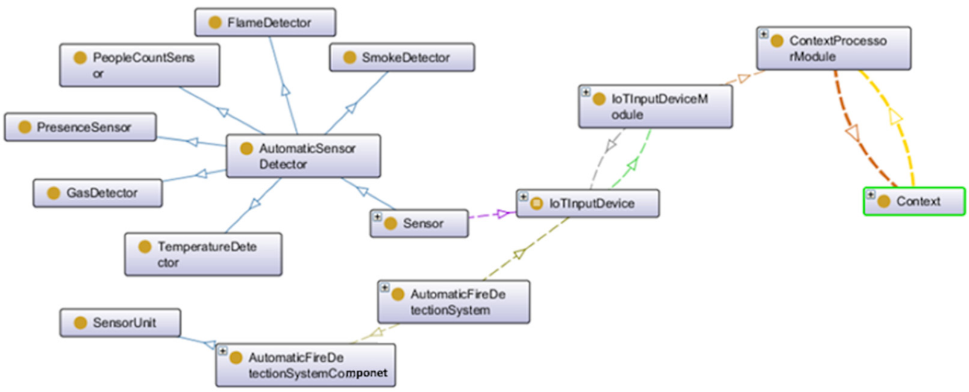


Figure 2. The contextual information construction process. Obtained from [25].

Based on the contextual information obtained through IoT, it is possible to build a solution capable of providing the building's occupants with updated information on safe evacuation routes, ensuring greater efficiency in building evacuation. Thus, the occupants use that information received in real time in their decision making about the most appropriate and safest evacuation route, adapting their behaviour to the recommended routes instead of adopting ways that may be conditioned or blocked because of the fire.

3.3. Occupants' Travel Speed

It has already been mentioned that the solution proposed here fits into phase 3 of the evacuation process and aims to reduce the occupants' movement time. Therefore, knowing how fast the occupants move during a fire emergency is essential. So, two approaches were identified in the literature to calculate the occupants' speed; both are presented below.

One approach follows the study of Coelho [3] and the PD 7974-6:2019 standard [5] and considers the following expression:

$$V = k\,(1 - \alpha D) \tag{3}$$

where

V is the evacuation speed (m/s);

k is the constant dependent on the type of evacuation route;

D is the density in number of people per square meter (p/m^2)

α is the constant equal to 0.266.

According to the PD 7974-6:2019 standard [5], for a density $D < 0.54\ p/m^2$, the building occupants move without constraints, unaffected by the other occupants of the space if evacuation routes are not subject to other risk factors resulting from the fire. However, according to the same standard, the occupants stop moving for densities higher than $3.8\ p/m^2$, leading to roadblocks and bottlenecks.

Defining standard evacuation speed (V_s) as the speed at which an occupant would move in a fire emergency, on a non-congested route, or with low occupancy density, then, from expression (3) and Table 1, we can construct Table 2. A value of 0.54 p/m^2 is considered for density D, as it is the density limit for unimpeded movement [5].

Table 1. Values of constant k for different types of evacuation routes. Adapted from [3].

Evacuation Route Type			k
Corridor			1.40
Galleries			1.40
Ramps			1.40
Doors			1.40
	Riser (cm)	Tread (cm)	
Stairs	19.05	25.04	1.00
	17.78	27.94	1.08
	16.51	30.48	1.16
	16.51	33.02	1.23

Table 2. Values of V_s speed for different types of evacuation routes.

Evacuation Route Type			k	V_s (m/s)
Corridor			1.40	1.20
Galleries			1.40	1.20
Ramps			1.40	1.20
Doors			1.40	1.20
	Riser (cm)	Tread (cm)		
Stairs	19.05	25.04	1.00	0.86
	17.78	27.94	1.08	0.92
	16.51	30.48	1.16	0.99
	16.51	33.02	1.23	1.05

The other approach to determining the occupants' movement speed considers the study by Predtechenskii and Milinski [4], based on building evacuation exercises and fire occurrences, with a particular focus on the movement of people in buildings, whether in everyday situations or fire emergencies. However, instead of using density D as defined in the previous approach, Predtechenskii and Milinski [4] introduced the concept of dimensionless density (D_a), which is based on what the authors define as the horizontal projection (P_h) of an occupant. Thus, considering a space or section of a route with a specific area (A) and considering N people on that section, the dimensionless density D_a can be defined as:

$$D_a = \left(\sum (P_{hi})\ |_{i:\,1\,...\,N}\right)/A \tag{4}$$

As follows from its definition, a person's P_h value varies according to their physical characteristics, age, clothing type, or what they are carrying in their arms. Table 3 presents the values calculated by Predtechenskii and Milinski [4].

In their study, Predtechenskii and Milinski [4] defined the speed (V) of an occupant as a function of the dimensionless density (D_a), considering the expression (5) for the standard speed in horizontal movements.

$$V = 112 \times {D_a}^4 - 338 \times {D_a}^3 + 434 \times {D_a}^2 - 217 \times D_a - 57 \tag{5}$$

Table 3. Average values for the horizontal projection (P_h) of a person. Adapted from [4].

Age	Clothing Depending on the Time of Year	Average Width (m)	Average Thickness (m)	Horizontal Projection (m^2)
Adult	Summer Mid-season Winter	0.460 0.480 0.500	0.280 0.300 0.3200	0.100 0.113 0.125
Young		0.430–0.380	0.270–0.220	0.090–0.067
Child		0.340–0.300	0.210–0.170	0.056–0.040
Adult	W/child in arms W/luggage in hand W/backpack W/light package in hand	0.750 0.900–1.100 0.500 0.750	0.480 0.750 0.800 0.400	0.285 0.350–0.825 0.315 0.235

From the previous expression, Predtechenskii and Milinski [4] introduce correction factors to determine the expressions for the vertical and span crossing circulations for three different types of movement—normal, comfortable, and emergency—which are shown in Table 4.

Table 4. Speed expressions according to the Predtechenskii–Milinski model for different movement and circulation conditions. Adapted from [3].

Movement Conditions	Circulation Conditions
	Horizontal circulation speed (m/min)
Normal	$V = 112 \cdot D_a^4 - 338 \cdot D_a^3 + 434 \cdot D_a^2 - 217 \cdot D_a + 57$
Comfortable	$V_c = (0.63 + 0.25 \cdot D_a) \cdot V$
Emergency	$V_e = (1.49 - 0.36 D_a) \cdot V$
	Speed on stairs (ascending) (m/min)
Normal	$V_a = V \cdot \left[0.785 + 0.09 \cdot e^{-3.45 D_a} \cdot sen(15.7 \cdot D_a)\right]\ if\ D_a \leq 0.6$ $V_a = V \cdot [0.785 - 0.10 \cdot sen(7.85 D_a + 1.57)]\ if\ D_a \geq 0.6$
Comfortable	$V_{ac} = 0.76 \cdot V_a$
Emergency	$V_{ae} = 1.21 \cdot V_a$
	Speed on stairs (descending) (m/min)
Normal	$V_d = V \cdot \left[0.775 + 0.44 \cdot e^{-0.39 D_a} \cdot sen(5.61 D_a + 0.224)\right]$
Comfortable	$V_{dc} = 0.76 \cdot V_d$
Emergency	$V_{de} = 1.21 \cdot V_d$
	Speed through doorways (m/min)
Normal	$V_v = V \cdot [1.17 + 0.13\ sen(6.03 D_a - 0.12)]$
Comfortable	$V_{vc} = V_v \cdot (0.63 - 0.25 D_a)$
Emergency	$V_{ve} = V_v \cdot (1.49 - 0.36 D_a)$

As with the previous approach, we will also calculate the standard evacuation speed (V_s) using the Predtechenskii–Milinski [4] approach.

Having as a reference a value of 0.54 p/m^2 for the density D and considering that from the definitions of D_a and D, one can obtain expression (6); also, considering the values in Tables 3 and 4, one can build Table 5, which presents the values of V_s for different types of journey and occupant's characteristics.

$$D_a = D \cdot P_h \quad (6)$$

Table 5. Values of V_s according to the Predtechenskii–Milinskii model in case of a fire emergency.

Characterisation of Occupants		Dimensionless Density (D_a)	V_s Movement Speed in an Emergency (m/s)			
Age	**Clothing Depending on the Time of Year**	**D_a For D = 0.54 m/s**	**Horizontal Circulations**	**Stairs (Ascending)**	**Stairs (Descending)**	**Doorways**
Adult	Summer	0.0540	1.14	0.79	0.93	1.36
	Mid-season	0.0610	1.11	0.77	0.92	1.33
	Winter	0.0675	1.08	0.76	0.91	1.30
Young		0.0486–0.0362 *	1.19	0.82	0.95	1.42
Child		0.0300–0.0216 *	1.28	0.85	0.97	1.50
Adult	W/child in arms	0.1539	0.78	0.54	0.75	0.99
	W/luggage in hand	0.1890–0.4450 *	0.51	0.34	0.50	0.66
	W/backpack	0.1701	0.74	0.51	0.72	0.94
	W/light package in hand	0.1269	0.86	0.60	0.80	1.08

* The average value was used to calculate the speeds.

Based on the PD 7974-6:2019 [5] standard and the studies of Coelho [3] and Predtechenskii and Milinskii [4], this section presented two ways to calculate the occupants' movement speed during the evacuation process of a building in the event of a fire emergency. The following sections demonstrate how these models can support a solution capable of guiding the occupants of a building to a safe place.

3.4. Modelling Contextual Factors

As previously mentioned, the changes in the building's environmental conditions in the event of fire result from two types of contextual factors: the factor of congestion of routes due to the accumulation of people and the hazard factor resulting from fire propagation related to the flow of smoke, toxic gases, and temperature increase. This section presents calculation models for both types of factors.

3.4.1. Model to Calculate the Contextual Factor Due to Congestion

As a result of a fire outbreak, the high density of people in a specific section of a building evacuation route leads to constraints that make it difficult for occupants to move and consequently reduce the speed at which they move to leave the building. This congestion tends to become worse close to exits or doorways, which can lead to total blockage due to the impossibility of movement [3].

As shown in Figure 2, these constraints can be detected using IoT devices equipped with sensors and detectors, such as presence detectors or people counting detectors, which allow for determining the density of people in each section of a pathway and, consequently, the time delay it causes.

To calculate this delay time, we will use the concept of specific flow (Fe), defined by [3] as the number of people passing through a section of an evacuation route per unit of time and unit of effective width of that section, and is given by the following expression:

$$Fe = V \times D \quad (7)$$

where V is the evacuation speed in meters per second and D is the population density in persons per square meter.

The total flow (F), being the product of the specific flow by the section width (L) [3], can be written as:

$$F = V \times D \times L \quad (8)$$

According to [3], the time required for a group of people (P) to cross a doorway of effective width L_e is given by the expression:

$$T = P/F = P/(V \times D \times L_e) \quad (9)$$

As previously mentioned, if we consider that in a non-congested section, that is, where an occupancy density is lower than 0.54 p/m^2, the occupants move at speed V_s, according to Tables 2 and 5, then in a congested section, the time T given by expression (9) can be understood as the time delay for crossing this section. Therefore, time T can be used to support decision making by a system with the objective of informing occupants about the more efficient evacuation routes.

3.4.2. Model to Calculate the Contextual Factor Due to Hazard

In addition to the constraints resulting from the overcrowding of people, there are also constraints resulting from the fire's combustion. Therefore, this section describes how to assess the impact on the occupants' movement resulting from hazardous situations caused by the development and spread of fire, namely regarding the existence of smoke, flames, toxic gases, and heat.

According to the PD 7974-6:2019 [5] standard, smoke causes a decrease in the occupants' movement speed, either by reducing visibility or by toxicity or irritation of the respiratory tract, making it possible to identify a set of conditioning aspects of occupants' ability and willingness to enter or move under smoke [5]:

- Each specific situation must be considered: whether the occupants are already immersed in the smoke and moving away from the fire or if smoke is already in the evacuation route.
- If immersed in the smoke, the occupants tend to move through the smoke, avoiding going in if alternative evacuation routes exist.
- Each person will have their own sensitivity to the smoke, so this is a personal decision. However, occupants with greater sensitivity tend to avoid moving through the smoke.
- Occupants also make decisions based on smoke density and visibility, tending not to walk through smoke in conditions of high uncertainty.
- Smoke with properties that irritate the people's airways is another aspect influencing occupants' decisions.
- Smoke temperatures that cause pain and discomfort tend to make occupants avoid moving in the smoke, looking for alternative routes

Table 6, obtained from [5,6], summarises the effects of smoke on occupant visibility and speed.

Table 6. The influence of smoke on occupants' visibility and speed. Adapted from [5,6].

Smoke Density and Irritancy Dm^{-1} (Extinction Coefficient)	Approximate Visibility Diffuse Illumination	Reported Effects
None	Unaffected	Walking speed of 1.2 m/s
0.5 (1.15) non-irritant	2 m	Walking speed of 0.3 m/s
0.2 (0.5) irritant	Reduced	Walking speed of 0.3 m/s
0.33 (0.76) mixed	3 m approx.	30% of people turn back rather than enter the smoke area
Suggested tenability limits for buildings:		
Small enclosures and travel distances: Dm^{-1} = 0.2 (visibilities of 5 m) Large enclosures and travel distances: Dm^{-1} = 0.08 (visibilities of 10 m)		

In addition to the problems caused by smoke, there is also the situation arising from occupants' exposure to toxic and asphyxiating gases. These gases can be incapacitating for building occupants. The PD 7974-6:2019 [5] standard refers to a relationship between the density of smoke and the concentration of irritating and asphyxiating gases. According to that standard, for the proposed limit of Dm^{-1} = 0.2, most fires concerning asphyxiating gases remain bearable for 30 min.

The PD 7974-6:2019 standard also has reference values for the maximum permissible concentrations of toxic gases, such as carbon dioxide, carbon monoxide, and hydrocyanic acid, formed during a fire. Table 7 presents values for the acceptable limits of CO, in parts per million, for fire whose combustible material has an estimated nitrogen content lower or higher than 2% of the total mass of these materials.

Table 7. Tenability limits exposure concentrations for asphyxiant gases expressed as carbon monoxide for five and 30-min exposures. Adapted from [5].

Category	Maximum Asphyxiant Concentration as CO 5 min Exposure µL/L	Maximum Asphyxiant Concentration as CO 30 min Exposure µL/L
Nitrogen > 2% by mass of fuel $\left(\frac{CO}{HCN} = \frac{12.5}{1}\right)$	800	125
Nitrogen < 2% by mass of fuel $\left(\frac{CO}{HCN} > \frac{50}{1}\right)$	1200	275
For both cases: $\frac{CO_2}{CO} = \frac{10}{1}$		

Heat is another critical factor limiting the occupants' movement and decision to proceed along a given route. The temperature resulting from a fire can reach values that are not bearable to the human body. The PD 7974-6:2019 [5] standard proposes limits humans can tolerate based on the pain resistance time for unprotected skin. These limits are presented in Table 8; still, according to [5], when a high percentage of water vapour in the air exists, as in places with sprinklers, the maximum tolerable temperature is 60 °C.

Table 8. Tenability limits for radiative and convective heat. Adapted from [5].

Mode of Heat Transfer	Intensity	Tolerance Time
Radiation	<2.5 KW/m^2	>5 min
	2.5 KW/m^2	30 s
	10.0 KW/m^2	4 s
Convection	<60 °C 100% saturated	>30 min
	100 °C <10% H_2O	8 min
	110 °C <10% H_2O	6 min
	120 °C <10% H_2O	4 min
	130 °C <10% H_2O	3 min
	150 °C <10% H_2O	2 min
	180 °C <10% H_2O	1 min

All three factors (smoke, toxic and asphyxiating gases, and heat) can be measured using appropriate sensors integrated into IoT devices. The data obtained can support a solution capable of informing the occupants of a building about the most suitable routes at any given time, thus allowing for conditioning their behaviour and guiding them to a safe place.

From Tables 6 and 7, Table 9 summarises the impact of smoke and heat on occupants' movement during the building evacuation process, bearing in mind that, as mentioned in

PD 7974-6:2019 [5] standard, for smoke density greater than 0.2 Dm^{-1}, the probability of irritating and even asphyxiating gases is high.

Table 9. Impact of the smoke and heat on occupants' movement. Adapted from [6].

Hazard Factor	Impact on Occupant's Movement
Smoke	According to [5], an occupant can move through the smoke if the smoke density is below 0.2 Dm^{-1}. However, the occupant's speed is reduced to 0.3 m/s (Table 6), so the occupant takes more time to travel across the smoke-affected area.
	The model herein proposed considers that If $Dm^{-1} > 0.2$, there are no conditions to enter or travel the area with smoke mainly because, according to [5], the existence of irritating or asphyxiating gases is very likely, so the section of the evacuation route must be considered blocked.
Heat	The occupants can travel the routes where the cold smoke layer temperature is below 60 °C. For higher temperature values, the presence of people is possible, but only in situations where they are already in the affected area. They should avoid entering into sections with temperatures above 60 °C.

3.4.3. Representing a Building as a Graph

According to [6,28], a floor building may be represented by a graph consisting of V vertices and E edges (Figure 3). These vertices and edges represent all the walkable areas of the building; the weight of the edge is the distance between two adjacent vertices, representing a section of an evacuation route. Alternatively, the weight of the edge can also represent the time it takes to travel that distance.

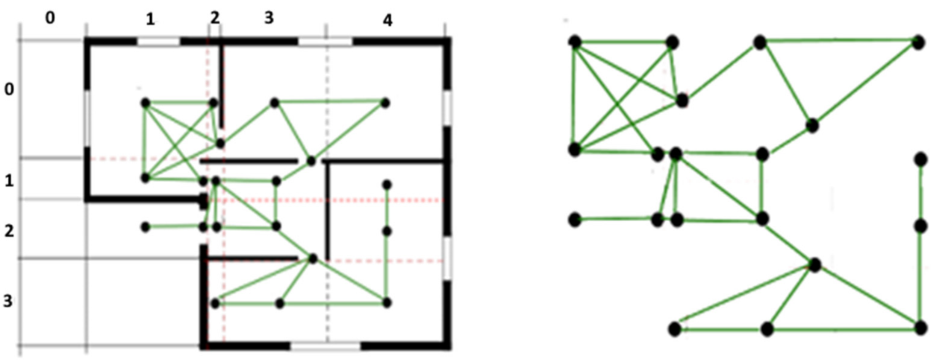


Figure 3. Representing a building with a graph. Obtained from [28]. Black dots and green lines are the vertices and the graph's edges, respectively.

When transforming the floor plan into a node network, each cell and doorway are represented by its geometric centre, as shown on the left side.

Thus, by installing IoT sensors throughout the building, data are obtained that reflect the environmental conditions of the different building sections that make up the evacuation routes, whether in terms of congestion of routes or concerning smoke, toxic and asphyxiating gases, and heat. These sensor data translate the constraints in the walkable areas of a building so that a building can be represented by a dynamic graph, with the computational representation presented in [6]. The dynamic graph consists of a matrix of adjacencies (MA) and a matrix of distances, or weights, (MD), so the dynamic graph G(t) can be written in the form [6].

$$G(t) = (MA(t); MD(t)) \tag{10}$$

The MD(t) matrix reflects the weight of the edges (sections of the evacuation routes) of the graph over time and can be written in the form [6]:

$$MD(t) = (MD_0; MFc(t)) \quad (11)$$

where MD_0 is the initial distance matrix (t = 0), and MFc(t) is the matrix resulting from the impact of the contextual factors presented in Sections 3.4.1 and 3.4.2. Therefore, it can also be written that [6]:

$$md((i,j),t) = (md_0(i,j) + mfc((i,j),t)) \quad (12)$$

where md(i,j), $md_0(i,j)$ and mfc(i,j) refer to the weight values for the section between the vertices i and j.

The resulting model of the impact of the hazard factors presented in Section 3.4.2 is summarised in Table 10.

Table 10. Risk level table: The impact on occupants' movement and on the building's graph. Adapted from [6].

Risk Level	Impact on Occupants' Movement	Impact on Building's Graph MFc(t) Values
0	The occupants move at normal speed.	The graph is not affected.
1	It reflects the existence of smoke but with a reduced impact on the occupants' movement. An occupant will continue his way through the smoke.	It is assumed that the occupants' speed decreased by 20%. Which is equivalent to a 20% increase in the initial weight of the corresponding edge (route section). $mfc((i,j),t) = 0.2 \times md_0(i,j)$
2	These levels reflect that smoke density and heat are already noticeable. Therefore, those in the area will continue their way if the bearable limits are ensured.	It is assumed an occupant 50% speed decrease, which is equivalent to doubling the length of the section: $mfc((i,j),t) = 1.0 \times md_0(i,j)$
3		It is assumed that an occupant's speed decreases from 1.2 m/s to 0.3 m/s, which is equivalent to multiplying by four the length of the section, so: $mfc((i,j),t) = 3.0 \times md_0(i,j)$
4	In these route sections, the factor values exceed the bearable limits for people and are blocked.	The interdiction of the section reflects on the adjacency matrix (MA)—nodes i and j are no longer adjacent—and in the MFc(t) matrix, and: $ma((i,j),t) = 0, mfc((i,j),t) = \infty$
5		

4. Testing the Models: Experiments and Results

The contextual factor models presented in the previous sections supported the development of an evacuation route recommendation solution based on a context-based multi-agent recommender system developed within the scope of our PhD thesis. In this section, we start by introducing the recommendation approach and the Evacuation Route Multi-Agent Recommender System (ERMARSys). Section 4.2 describes the experimental scenarios, and the results are presented in Section 4.3.

4.1. The Evacuation Route Multi-Agent Recommender System

The recommender solution, detailed in [6], assumes the installation of IoT input devices to collect data regarding the building's environmental conditions and IoT output devices to present building occupants with the most appropriate and efficient routes at every moment. The data collected by the sensors are used to dynamically update the building graph to reflect the status of the evacuation routes at every moment. With this contextual information reflected in the building's dynamic graph, the recommender system provides occupants with the most efficient and safe routes at each moment. Figure 4 presents the architecture of the recommender solution [6].

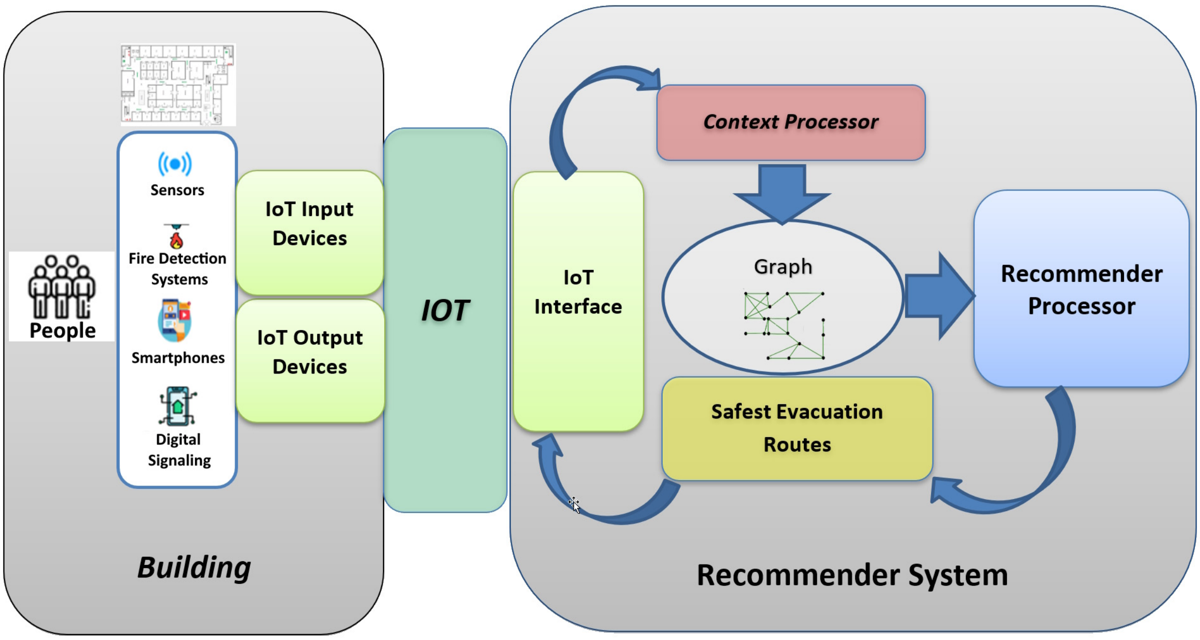


Figure 4. The global architecture of the context-based recommender solution. Obtained from [6].

Based on the architecture of Figure 4 and the models presented in Sections 3.4.1–3.4.3, it was developed a prototype of the ERMARSys [6], whose global architecture is shown in Figure 5 [6].

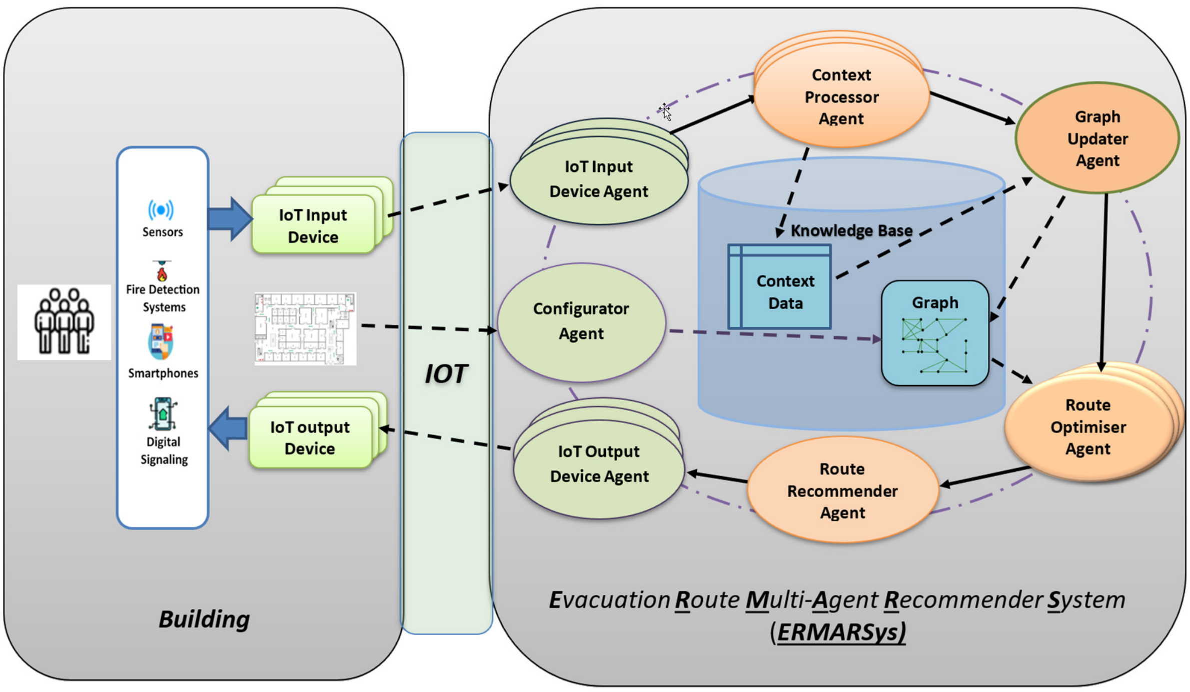


Figure 5. The architecture of the multi-agent-based recommender solution. Obtained from [6].

The ERMARSys system, presented in detail in [6], is a context-aware multi-agent recommender system based on contextual information built from IoT sensor data obtained in real time. This contextual information characterises the environmental conditions of the building at every moment and is used to update the dynamic graph that represents the building in the recommender system. Based on the graph, the recommender system determines the most efficient and safe evacuation routes, presenting them to the building occupants by dynamic digital signalling.

4.2. Experimental Scenarios

The ERMARSys system was tested on the Web simulation platform developed according to [28,29], and the experimental scenarios and results are described and presented in detail in [6].

This paper summarises the experimental scenarios and results, highlighting the contribution of the models of contextual factors.

Figure 6 presents a screenshot of the Web simulation platform, representing the building (LNEC congress centre area) under testing.

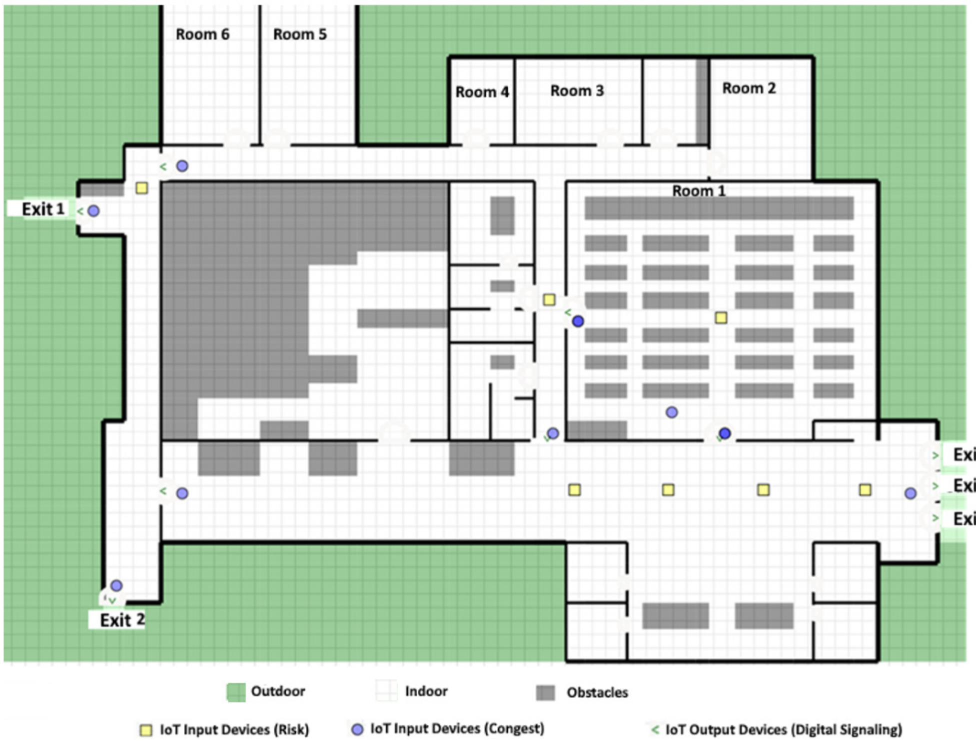
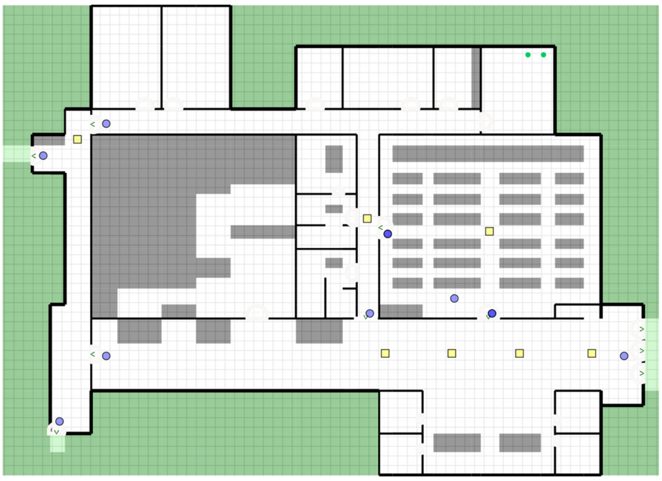


Figure 6. Screenshot of the Web simulation platform, representing the floor plan of the LNEC congress centre. Obtained from [6].

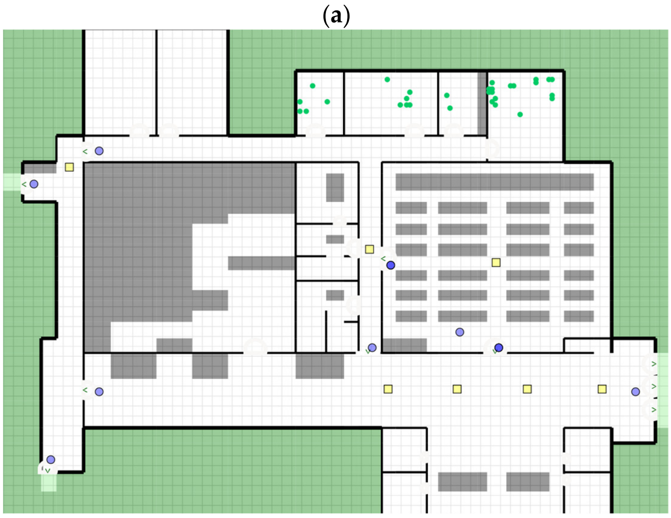
The LNEC congress centre has an area of about 2000 m^2 with a capacity of 300 people. The congress centre has a main room for about 200 seated people plus five rooms with an average capacity of 20 people.

For the tests and simulations, the following scenarios were considered: (i) Scenario 1 considers two occupants in room 2; (ii) Scenario 2 considers 30 occupants occupying rooms 2 to 4; (iii) Scenario 3 considers 200 occupants randomly positioned.

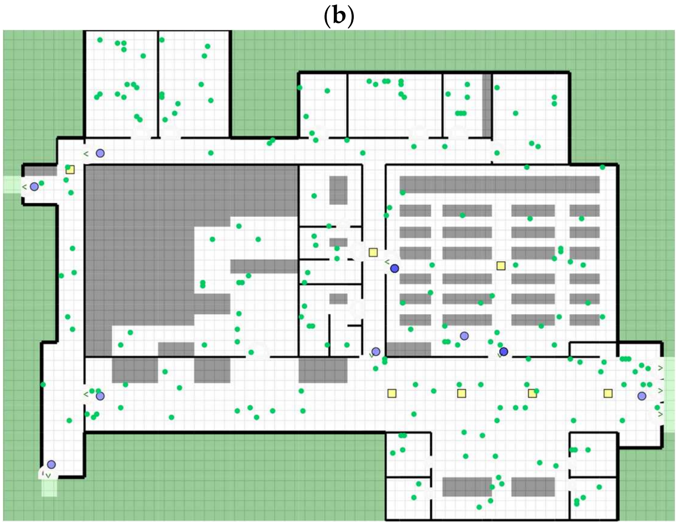
For each of the above scenarios, the following situations were considered: (i) occupants know the building and do not follow emergency signs; (ii) none of the occupants knows the building, so they move to the exit following the static emergency signs or those recommended by ERMARSys, if active. Figure 7 shows the occupants' initial position for each scenario.



(**a**)



(**b**)



(**c**)

Figure 7. Occupants' initial position (green dots): (**a**) Scenario 1—two occupants positioned in room 2; (**b**) Scenario 2—30 occupants occupying rooms 2 to 4; (**c**) Scenario 3—200 occupants randomly positioned.

4.3. Results

The results are presented considering two points of view: the time it took the occupants from starting the movement until reaching a safe place and the building evacuation pattern followed by the occupants.

Table 11 and Figure 8 show the results for all the mentioned scenarios and situations concerning the movement time. The results show that for all scenarios, the introduction of the ERMARSys recommender system makes it possible to evacuate the building in less time.

Table 11. Occupants' movement time for each simulated scenario and situation.

	Scenario 1	Scenario 2	Scenario 3
	Two occupants in room 2	30 occupants in rooms 2 to 4.	200 occupants randomly positioned
All occupants know the building	71.31 s	88.78 s	97.82 s
Occupants do not know the building (without ERMARSys)	61.13 s	95.41 s	100.25 s
Occupants do not know the building (with ERMARSys)	57.88 s	60.3 s	80.53 s

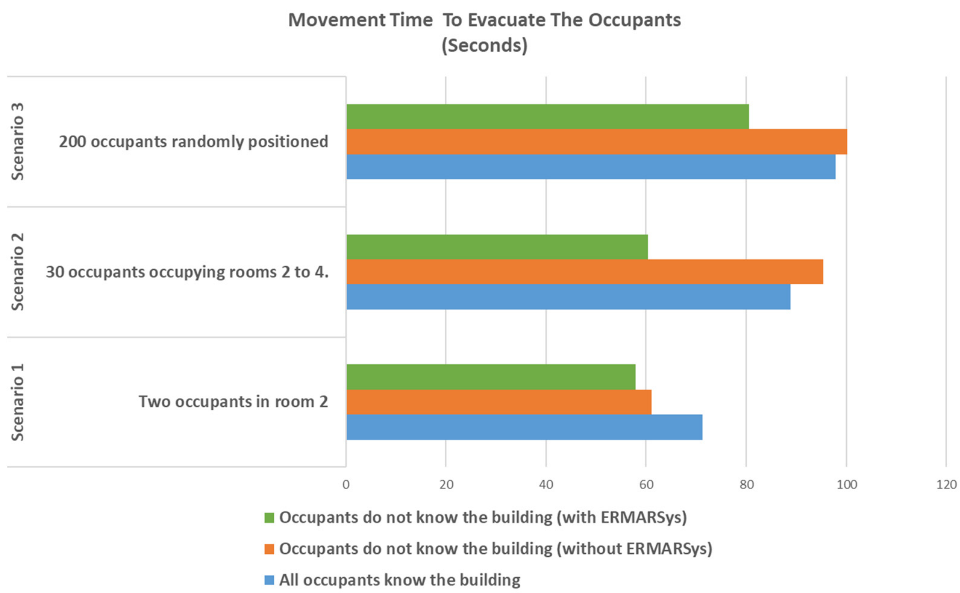


Figure 8. Required movement time to evacuate the occupants for all simulated scenarios.

Concerning the evacuation patterns for the simulated situations, shown in Figure 8, it is possible to verify that in cases where the ERMARSys system is inactive, more occupants need to reverse their direction of movement. So, occupants who do not follow the dynamic emergency signs updated by ERMARSys only later become aware of the blockage of exit 1, as can be seen by comparing the areas inside the blue areas in Figure 9. On the other hand, when the ERMARSys system is active, all the constraints and the blockage of exit 1 are reflected in the recommended evacuation routes.

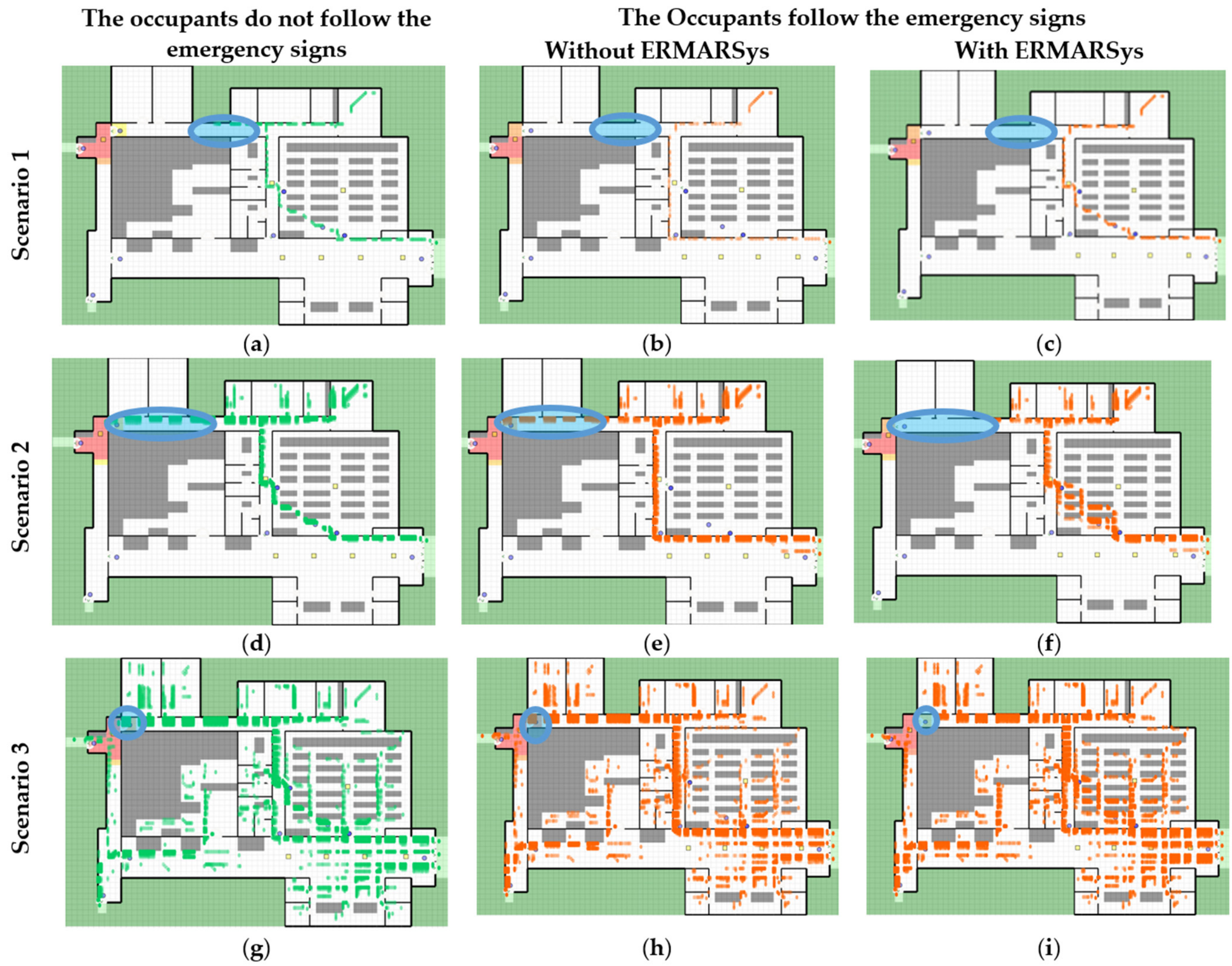


Figure 9. The evacuation routes that the occupants have taken for all three scenarios and simulated situations. Green and orange dots represent the occupants' movement. The blue areas include the occupants that need to return due to the blockage of exit 1. (**a**) If both occupants are familiar with the space and do not follow the emergency signs; (**b**) if the two occupants follow static signalling; ERMARSys inactive; (**c**) if both occupants follow ERMARSys recommendations; (**d**) if the 30 occupants are familiar with the space and do not follow the emergency signs; (**e**) if the 30 occupants follow static signalling; ERMARSys inactive; (**f**) if the 30 occupants follow ERMARSys recommendations; (**g**) if the 200 occupants are familiar with the space and do not follow the emergency signs; (**h**) if the 200 occupants follow static signalling; ERMARSys inactive; (**i**) if the 200 occupants follow ERMARSys recommendations.

5. Discussion

The time it takes to evacuate a building in case of fire is crucial to ensure the safety of occupants and to optimise the fire safety solutions to be adopted. However, its rigorous calculation is subject to significant uncertainty arising from people's behaviour in these situations, which causes longer and less rigorous evacuation times.

As Cordeiro [2] mentions in his study on human behaviour in the case of fire, occupants spend time making decisions and performing tasks before deciding to leave the building. These actions, which do not have the immediate objective of leaving the building, can sometimes make it difficult to evacuate, increasing the danger to which the occupants are exposed. The time consumed in making decisions and performing these tasks significantly influences the total evacuation time.

In addition to the fact that we rarely know the characteristics of the occupants of a building, especially in those where the population is essentially fluctuating, it is extremely difficult to know the occupants' behaviour accurately. Thus, considering the difficulties in accurately modelling the behaviour of occupants, we propose a new paradigm that, using up-to-date information on the environmental conditions of a building, provides occupants with safe evacuation routes, helping them to make decisions about the evacuation route to take to exit the building, thus contributing to more occupants' predictable behaviour.

The solution presented in this paper, which consists of using information about the environmental conditions of the building to help the occupants choose the escape routes that will most help them exit from the building, contributes to reducing the time consumed in decision making.

The results suggest that, for any of the simulated scenarios, the ERMARSys recommender system ensures that the evacuation is carried out in less time, thus contributing to greater efficiency of the evacuation process. This greater efficiency is reflected in the fact that occupants need less time to leave the building, and fewer of them need to reverse direction.

The results also show that in a fire situation that leads to constraints on evacuation routes, it is not enough for the occupant to be familiar with the building to choose the most efficient way. Even if the occupants know the area where the fire broke out, they will know nothing about the impact on evacuation routes. Supported by the models presented in Sections 3.4.1 and 3.4.2, the ERMARSys system is aware of environmental changes in the building in real time, allowing the recommendation of the most efficient evacuation routes at every moment.

It must also be noted that the simulations focused on the occupants' movement time as defined in Section 3.1—the time from the moment an occupant starts their movement to leave the building until they are in a safe location. It may also be said that the study presented here focuses on what was previously defined as phase 3 of the evacuation process. As already mentioned, the duration of this phase coincides with the movement time under study. It depends on the occupants' characteristics and their behaviour, the environmental conditions of the building, and how the fire affects evacuation routes.

With the solution presented here, it is possible to perceive changes in evacuation routes through IoT sensors installed in the building and use that information to make the occupants' behaviour more predictable by recommending the most appropriate evacuation routes.

The limitations of the study are mainly related to the assumptions considered in the development of the prototype of the recommender system and experimentation scenarios, namely:

- To determine the people density in an evacuation route section, a hypothetical sensor was used to calculate the number of occupants in that section.
- To determine the hazard factor, we used a hypothetical risk sensor capable of reproducing the effects of the fire (smoke, temperature, and toxic gases) on the evacuation routes.
- In the simulation, it was assumed that occupants do not exchange information with each other. Thus, if an occupant returns because an evacuation route is blocked, he/she does not give this information to the other occupants.
- In cases where the occupants are unfamiliar with the building, it was assumed on the simulations that they do not know anything about it. However, in a real situation, people at least register where they enter the building, so they tend to know at least that way out.

However, the above simplifications still made it possible to simulate changes in the building's environmental conditions and in the occupants' movement due to restrictions on evacuation routes without jeopardising the study's objectives.

6. Conclusions and Future Work

This research aims to study how real-time knowledge of the environmental conditions of a building could be used to positively influence people's behaviour while evacuating them from a building in case of fire.

Based on consolidated theoretical knowledge in the research area of building evacuation in case of a fire, this paper presents models of contextual factors to address congestion and hazardous issues arising from fire. These models were incorporated into the ERMARSys recommender system, and the simulation results suggest that they can contribute to the development of solutions capable of efficiently guiding the occupants of a building to a safe place.

The ability of a solution like the one presented in this article, which provides information on the most efficient evacuation routes, allows occupants to adapt their behaviour during their movement to leave the building, following the system's indications instead of acting on their own initiative, thus helping to exit the building safely.

Concerning future work, it is essential to deepen the study of models of contextual factors, namely about environmental conditions, using information from other models, such as, for example, the Consolidated Model of Fire and Smoke Transport (CFAST) of the National Institute of Standards and Technology (NIST). It is also essential to deepen the study about the dependence of the occupants' movement speed as a function of the occupation density. We also plan to test the proposed models on other simulation platforms like Pathfinder and FDS (Fire Dynamics Simulator).

It is also necessary to assess how people react to a system like the one proposed, especially concerning confidence in such an approach herein presented. It is essential to start by conducting surveys that make it possible to draw conclusions on this matter.

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Conflicts of Interest: The authors declare no conflict of interest.

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