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A smart spontaneous crowd evacuation system for large multi-exit exhibition centers based on IoT

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Abstract

Plans to mass evacuate visitors in an exhibition center in the case of emergency situations are critical for public safety and disaster management. Efficient crowd evacuation during mass gatherings has been an active research area during the past years. In this paper, we consider the challenging problem of finding in near real-time the most efficient and safest evacuation pathways in a multi-exit exhibition center while the fire hazard spreads. We first propose a system composed of sensor nodes to collect pertinent safety data associated with the changing environmental conditions. We then present a spontaneous dynamic evacuation system that considers the changing conditions in the risks associated with each hallway segment in terms of walking distance, heat, two major asphyxiant fire gases and crowd congestion. Our IoT-based system activates smart panels placed at major junctions of the hallways to visually guide evacuees towards the safest escape direction under the existing circumstances. The proposed algorithms aim to minimize the total evacuation time of all evacuees, while circumventing congested and perilous aisles, balancing traffic loads, and guaranteeing high scalability and reasonable computational efficiency. This work can pave the way towards the development of next-generation smart exhibition centers, where crowd safety is among the top priorities.

Keywords: *Evacuation system, crowd management, indoor navigation, smart exhibition center, fire evacuation, IoT*

1. Introduction

Hundreds of international trade fairs and exhibition events are organized each year. Some of these events attract thousands of visitors daily and they typically last between 3 to 15 days. For instance, in the realm of IT expos, some renowned international fairs are organized each year, including [1]:

- Gamescom interactive games and entertainment show (Cologne, Germany): 373,000 visitors in 2019.
- IFA global trade show (Berlin, Germany): 244,055 visitors in 2018.
- HANNOVER Messe (Hannover, Germany): 211,338 visitors in 2019.
- MWC Mobile World Congress (Barcelona, Spain): 109,000 visitors in 2019.
- CES international consumer electronics show (Las Vegas, USA): 100,783 visitors in 2019.
- GITEX technology week show (Dubai, UAE): 100,000 visitors in 2018.

Despite the large space availed to visitors in most exhibition centers (with Hannover exhibition center being the largest convention center in the world with a 554,000 sqm surface area), the sheer number of attendees often result in transient congestion situations that need to be carefully managed, especially during crisis situations such as fire blazes, bomb threats, armed assaults, or terrorist attacks. Aware of the importance to safeguard the safety of its visitors, major convention centers have adopted several measures to cope with emergency evacuations. These include the installation of emergency exits, fire hoses, extinguishers, alarm systems, and the development of emergency preparedness, response, evacuation, and assembly procedures. For the purpose of this study, we define emergency evacuation as the planning and the processes put in place to move people away from hazardous zones towards safety emergency exits in the shortest possible time. The goal is to ensure the safest and most efficient evacuation for all evacuees.

Exhibition centers are not prone to fires as demonstrated for instance by the massive blaze at the SkyCity convention center in Auckland in October 2019. In addition, a false fire alarm from a smoke detector (such as the one witnessed at the Anaheim Convention Center in August 2019) can trigger panic among visitors and the activation of emergency evacuation procedures. As a result, effective emergency response mechanisms must be put in place to swiftly evacuate visitors in order to save lives and reduce potential injuries due to people

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stumbling and trampling. However, while some visitors cannot even locate emergency exits, others find it difficult to identify the best escape route. For instance, an empirical study [2] revealed that nearly 80% of adult visitors do not recall the location of at least one emergency exit in a shopping mall in the city of Fiume Veneto, in Italy. We should also recognize that evacuation planning is a very intricate and multi-factor research problem that involves both features of individuals and environment [3]. The task to identify the closest and safest exit pathways gets even more complicated for visitors as the fire blaze and the released smokes can quickly propagate inside the exhibition center, obstructing visibility and leading to panic.

Motivated by the aforementioned observations, we propose a smart dynamic evacuation model for multi-exit exhibition centers in the presence of spreading fire blaze. Our dynamic evacuation system provides visual indications to evacuees to guide them towards best available paths while trying to circumvent dangerous zones. This work is part of the Ariadne Smart Exhibition Center project that aims to pave the way towards a new breed of intelligent exhibition centers by leveraging the usage of mobile computing, wireless sensors, image processing, web services and artificial intelligence. The proposed solution can provide support for emergency response personnel to reduce the risks of crowd stampedes and casualties in emergency situations involving pedestrian aggregation activities within closed areas. Although our approach is presented in the context of an exhibition center, it can be applied to other settings, including shopping malls, subway platforms, large museums, and stadiums where the mass evacuation of visitors under emergency situations is of paramount importance.

This research addresses two research questions. The first is how to estimate in real-time the degree of risk of an evacuation route. The second is how to determine the safest and most efficient escape routes.

Our approach addresses many limitations associated with most earlier contributions notably (1) the reliance on static fire hazard models, (2) the usage of static evacuation models that do not adapt to dynamic fire spreading behavior, (3) the narrow choice of parameters to characterize the risk associated with a given hallway, and (4) the non-applicability of the approach to real-life scenarios.

The remaining of this paper is organized as follows: In Section 2, we present a review of major related studies and highlight the contribution of this research. Section 3 presents the full details of our proposed approach. Finally, in section 4 we provide a summary of the paper and some recommendations for future research.

2. Related work and research contribution

The problem of massive evacuation during emergency situations has attracted considerable attention among researchers and practitioners. The goal of an evacuation system is to minimize the risks of harm and deaths among the public during emergencies. There has been a considerable number of scattered models and solution methods to calculate the best suited escape route in the case of single as well as multiple emergency-exits. Most of these approaches operate on graph-based models and they differ in many aspects, including:

- The graph modeling approach as reflected by the choice of the vertices and edges.
- The choice of the weights assigned to each vertex and the capability to handle dynamically changing routes.
- The choice of the algorithm to find the most suitable evacuation route.
- The general approach: optimization-oriented or computer simulation-oriented.
- Implementation approach: spontaneous evacuation plan versus organized evacuation plan [4].
- The architecture of the proposed solution (centralized versus distributed).

Li et al [4] classify evacuation plans into two categories: spontaneous evacuation plans and organized evacuation plans. Spontaneous evacuation plans are guided by the evacuation infrastructure such as fire emergency lighting and dispersal indicators. Organized evacuation plans, on the other hand, require personnel to control the flow of evacuees by dictating departure times, and routes to safe exits. This latter approach is however more difficult to implement.

Filippoupolitis and Gelenbe [5] proposed a distributed system that computes the best evacuation routes, while a hazard is spreading inside a building. The weight of each edge is the product of two variables: the physical length of the edge and the intensity of the associated hazard along the edge. However, the hazard intensity values collected from the sensor nodes remain undefined and it is not clear how these were used in the simulation model.

Shikhalev et al [6] proposed a decision support system to determine the safest route during an emergency. They formulated a multi-objective optimization model where the weight of each section in the route considers three criteria: obstruction (based on people density), timeliness (based on the fire hazard value) and length (based on the length of the section). The approach, however, is not suitable for implementation in real-life settings as (1) it aims to calculate the safest escape route for each person from his starting position to each safety area which is not practical, and (2) the solution is sensitive to various parameters including the value of the fire hazard on each section (which is not defined) and the weight coefficients associated with the cost of each edge.

Atila et al [7] proposed a mobile dynamic fire evacuation system based on 3-D spatial modeling. The microscopic model calculates the personal route for each evacuee by considering his/her individual route and provides visual instructions on the smartphone to guide each evacuee towards the most appropriate exit. Based on earlier studies on smartphone usability and human psychological reactions during emergency evacuations (e.g. [8]), we argue that the usage of mobile apps for evacuation is not practical due to the additional cognitive load imposed on users while they struggle to escape.

Some researchers adopted a graph theoretic network optimization approach by formulating the evacuation process as an optimization problem that aims to minimize the evacuation time of all evacuees under path capacity and fire smoke presence constraints (see for example [4]). Such models are however not suited for real-life deployments.

There have been works focusing on the study of spontaneous evacuation models, including dynamic minimum-cost flow network models [9], linear programming (LP) models [10] cellular-automata models [11], evolutionary algorithms [12], ant/bee colony optimization [13-14], fuzzy-logic approaches [15], game-theoretic frameworks [16-17] and Capacity Constrained Router Planner (CCRP) heuristic algorithms [18], among many others. Other researchers [e.g. [19]) opted for simulation-based approaches whereby evacuation route planning is based on simulating actual fire evacuation scenarios.

Contemporary trends in crowd evaluation include the usage of mobile sensing [20], robot-guided evacuation schemes [21], and mobile crowdsourcing [22]. Each of these approaches has its own merits and drawbacks. For a review of the relative merits of these approaches, the reader is referred to the survey papers of Zheng et al [23], Zhou et al [24], Kobes et al [25], Liu et al [26], Haghani [27] and Ibrahim et al [28], and Sharbini et al [29].

Our approach is based on a spontaneous evacuation plan that can adapt to changing conditions and operates at the macroscopic rather than microscopic (individual) level. Hence it does not require each evacuee to be equipped with a special device (such as a hand-held RFID reader as suggested in [7]) to acquire his location in real-time. Recall that microscopic models consider the evacuee's individual characteristics and interaction in the evacuation process, while macroscopic models are often based on network flow models [4]. Contrary to most earlier approaches that aimed to minimize the overall escape time of all evacuees, our approach takes also into account the safety risks associated with fire heat, toxic gases, and congestion.

Our contributions include the following:

- A novel graph model whereby hallway sections are modeled as links and junctions are modeled as nodes.
- A new approach for determining the escape plan. In our case, once a fire occurs, we measure the risk index of each hallway section at regular time intervals and direct evacuees at the junctions based on a constrained shortest path algorithm that aims to reduce the total risk along the evacuation pathway, as opposed to merely trying to minimize the total evacuation time, which could put evacuees at risk due to exposure to excessive heat or suffocation.
- The adoption of a more realistic model in computing the cost associated with each hallway section, which includes not only the distance but also the time-dependent risk associated with high temperature, level of toxic gases, and congestion levels. For this purpose, we propose a quantitative risk assessment model to estimate the risk indices associated with the hallways.
- Though our approach makes use of well-known shortest path algorithms, it introduces the usage of constrained based routing which prunes links that do not satisfy the minimum safety requirements prior to computing shortest paths.
- A mechanism to dynamically adjust the evacuation routes according to the evolving status of the fire propagation and the dynamic nature of crowd density during the evacuation. By taking crowd density into account in the computation of the shortest path, our approach offers the capability to steer the crowd away from congested hallways. This approach can gradually contribute to some sort of load balancing across the escape routes, avoiding congestion and hence reducing the emergency evacuation time. As highlighted by Li et al [16], congestion-related evacuation modeling has a significant impact on evacuation planning and hence needs to be an integral element of an evacuation system. Recall that mass-evacuation scenarios often lead to congested escape paths, which reduce the walking speed of the crowd, increases the probability of injuries and fatalities, and prolongs the overall evacuation time. In particular, bottleneck effect during emergency evacuations needs to be taken into account [30].
- The reliance on visual direction indicators, displayed on smart digital panels located at the junctions of hallways to guide evacuees towards the safer exits.

3. Proposed approach

Our proposed approach uses Wireless Sensor Networks (WSNs) to identify crowd turbulence by detecting overcrowded areas at different epochs during the evacuation procedure. We first outline the design aspects of the proposed system, including its underlying assumptions and its graph modeling approach.

3.1. General assumptions

Our proposed approach is based on the following assumptions:

- The detailed floor plan/layout of the exhibition center is known a priori.
- There are several sensor nodes installed at specific locations along the hallways of the exhibition center. For better fault tolerance, we adopt dual base station architecture for the WSN in a star-of-stars topology. The sensor nodes communicate with the two base stations (BS), which forward the collected data to a network server.

Each sensor node collects and sends real-time information to the base station which includes temperature, Carbon monoxide (CO), hydrogen cyanide (HCN) and crowd density levels.

- There are several smart digital panels at the junctions of the exhibition center (in each direction) which provides emergency signage in the form of a dynamic visual indicators.
- An application (Command-and-Control) server is put in place to communicate with the central server and to calculate the most suitable evacuation route to the most appropriate emergency exit.
- The Command-and-Control server conveys the suggested evacuation direction to each junction via the corresponding smart digital panel.
- All evacuees obey the exit directions proposed by the smart digital panels.

Fig.1 illustrates a simplified diagram of the system architecture.

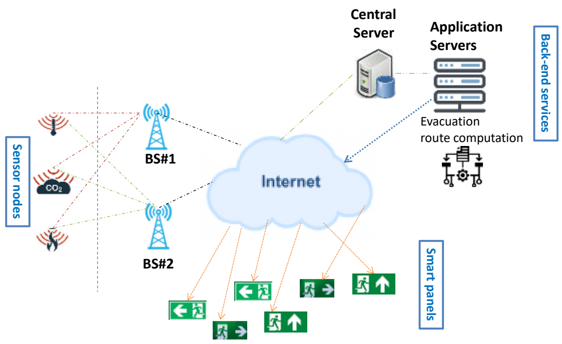

Fig.1. Simplified diagram of the system

3.2. Graph Modeling Approach

We illustrate the problem formulation, the modeling and solution approaches with the sample example depicted in Fig.2. As may be seen, the layout shows various stands (greyed boxes) and four emergency exits. The red circles correspond to the crossings of escape routes (major junctions) where smart digital panels are located to indicate the evacuation direction. The above plan is modeled by the graph G (N, E) depicted in Fig. 3.

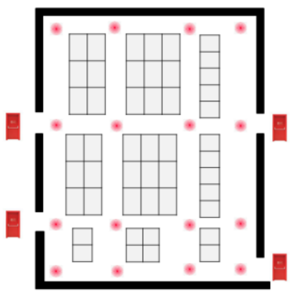

Fig.2. Illustrating example for the floor plan

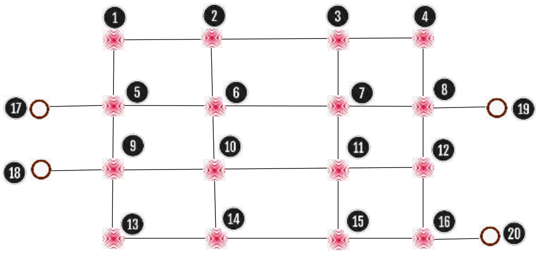

Fig.3. Graph modeling the plan shown in Fig.2

The graph consists of a set of 20 vertices where vertices 1-16 correspond to the crossings of escape routes (coinciding with the locations of the digital panels) and vertices 17-20 correspond to the four emergency exits. These vertices will be thereafter referred to as regular nodes and exit nodes, respectively. The graph also consists of 28 edges, each corresponding to a potential leg (hallway) along feasible escape routes that evacuees can follow. For each edge connecting nodes i and j, we assign a time-dependent weight value $W_t(i,j)$ which represents the cost of using link (i,j) at time t to escape towards one of the exits.

In our case, $W_t(i,j)$ is defined as a weighted average, according to the following expression:

$$W_t(i,j) = \alpha_1 L(i,j) + \alpha_2 P_t^T(i,j) + \alpha_3 P_t^{CO}(i,j) + \alpha_4 P_t^{HCN}(i,j) + \alpha_5 P_t^D(i,j) \quad (1)$$

where the weight coefficients $\alpha_i \in [0,1]$ sum up to 1. These coefficients reflect the relative importance of the associated variable in the evacuation decision making process. They are estimated based on collected fire and rescue statistics as well as expert judgments, as further explained at the end of this subsection. In Eq.1, $L(i,j) \in [0,1]$ represents the relative length of hallway segment (i, j), defined as the ratio of the length of link (i,j) to the length of the longest link in the graph. The terms $P_t^X(i,j) \in [0,1]$ correspond to the Risk Index $RI \in [0,1]$ associated with temperature (T), Carbon monoxide (CO), hydrogen cyanide (HCN), and people density (D), as further explained below. Obviously, in the presence of a fire hazard, the shortest physical length path does not necessarily imply the lowest risk, as a link (i,j) along the shortest path might be the subject of fire and/or smoke hazard and hence needs to be circumvented when computing the evacuation route.

In our case, some sensors are installed along each hallway section (i,j). These sensors monitor various parameters that are used as proxy-indicators of the risk associated with selecting hallway segment (i,j) in the escape route. When a given hallway-segment has multiple sensors of the same type (such as temperature), the highest reported value is considered in the computation of the link weight as this corresponds to the worst-case scenario.

Our proposed system monitors the following environmental and congestion-related parameters:

- Temperature: Each reported temperature value is converted into a risk index $P_t^T(i,j)$ according to Table 1. The ranges are inspired from the empirical work of Willi et al [31].

Table 1. Temperature - risk index conversion

Reported temperature T (°C)	Risk classification	Risk index $P_t^T(i,j)$
T < 48	Low	0
48 ≤**T** <50	Medium	0.5
50 ≤ **T** < 150	High	0.7
T ≥ 150	Very high	1

- Toxic (Asphyxiant) fire gases which include Carbon monoxide (CO) and hydrogen cyanide (HCN). Together, CO and HCN – recognized in the fire industry as the "toxic twins" – create a deadly chemical asphyxiant that can put fire victims into cardiac trauma [32].

Carbon monoxide poisoning is the most common type of fatal air poisoning during fire as carbon monoxide asphyxiation has been a leading cause of deaths for those overcome by smoke. The ranges for CO levels are based on the Acute Exposure Guideline Levels (AEGLs) for exposure times of 10 minutes and 30 minutes [33]. For instance, exposure for 10 minutes to a level of CO at or above 420 ppm can yield serious long-lasting effects or impaired ability to escape [33]. CO reported values are converted to risk index $P_t^{CO}(i,j)$ according to Table 2.

Table 2. CO level – risk index conversion

Reported CO level (ppm)	Risk classification	Risk index $P_t^{CO}(i,j)$
CO < 150	Low	0
150 ≤**CO** <420	Medium	0.5
420 ≤ **CO** < 600	High	0.7
CO ≥ 600	Very high	1

Hydrogen cyanide (HCN) is a colorless, rapidly acting, highly poisonous gas that is 35 times more toxic than CO [33]. The ranges for HCO levels depicted below are derived based on the studies reported in [34]. HCN reported values are converted to risk index $P_t^{HCN}(i,j)$ according to Table 3.

Table 3. HCN level – risk index mapping

Reported HCN level (ppm)	Risk classification	Risk index $P_t^{HCN}(i,j)$
HCN < 36	Low	0
36 ≤**HCN** <108	Medium	0.5
108 ≤ **HCN** < 135	High	0.7
HCN ≥ 135	Very high	1

- Congestion, as measured by human density, is a determinant factor of crowd dynamics and evacuee's walking speed, and hence it has strong influence on the evacuation time [7]. The density, D, along a given hallway section is estimated as the number of people inside its circulation divided by the area. The number of people present in each hallway can be estimated using different methods: Bluetooth scanning methods [35-36], dynamic computer vision-based tracking [37], RFID technology [38], and Infrared (IR) transmitters and receivers [39]. We recommend the usage of IR transmitter and receiver pairs as it is reliable, and it provides a low-cost, yet accurate method to estimate the number of evacuees within a given hallway. The ranges for the density ranges depicted in Table 4 were chosen based on the results reported in [28]. For instance, density of 6 persons/m^2 corresponds to a critical crowd density for moving (i.e., evacuees will be able to move slowly by exerting pressures on each other) [28]. A density of 7.1 persons/m^2 corresponds to the maximum crowd density while standing.

Human density values are converted to risk index $P_t^D(i,j)$ according to Table 4.

The weights α_i in Eq.1 were determined based on reported fire and rescue statistics and expert judgements as follows:

In [40] it was highlighted that HCN is 33–35% more dangerous than CO. Hence, we perceive HCN risk 1.35 times as important as CO risk.

Table 4. Density – risk index mapping

Reported density (person/m²)	Risk classification	Risk index $P_t^D(i,j)$
D < 4	Low	0
4 ≤**D** <5	Medium	0.5
5 ≤ **D** < 7	High	0.7
D ≥ 7	Very high	1

Heat exposure from a fire can trigger skin burns, incapacitation, and death in many forms: heat stroke (hyperthermia), body surface burns, and respiratory tract burns [41]. Accordingly, we perceive CO risk 1.5 times as important as air temperature T risk.

Congestion buildup due to high people density inhibits people movement and hence extends the evacuation time. Because of congestion, the shortest path (in terms of physical distance) is not necessarily the shortest evacuation path. Hence, we perceive people density D risk as being twice as important as the relative physical length factor and 0.5 times as important as air temperature T risk.

Based on the above, we derive the following values for the weight coefficients α_i :

α_1=0.05; α_2=0.19; α_3=0.28; α_4=0.38; α_5=0.10

3.3. Safest route algorithm

A core component of our safest route algorithm is the constrained shortest path algorithm described below. Given a weighted graph *G* (*N*, *E*) of the type shown in Fig.3, the objective is to compute the shortest path between each regular node and the closest exit node. This is equivalent to adopting a heuristic approach to generate most effective/safest evacuation pathways in the shortest possible time. To reduce the complexity of the shortest path computation, we decided not to use Floyd-Warshall's algorithm to find the shortest path for every regular source node and exit node, followed by selecting the shortest one. Instead, we will transform the original graph *G* into a new graph *G'*(*N'*,*E'*) by adding a dummy vertex D which is connected to each exit node via a link of weight 0. Fig.4 illustrates the transformation corresponding to the original graph shown in Fig.3.

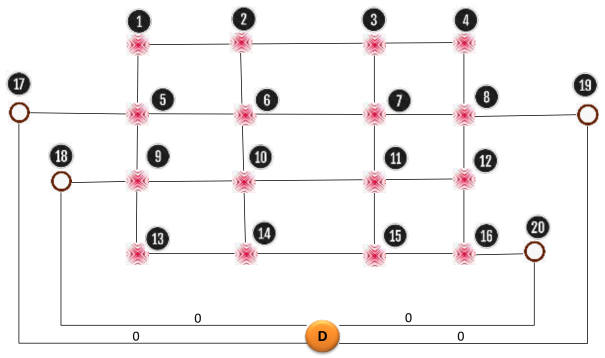

Fig.4. Graph transformation

With this transformation, the problem reduces to finding the shortest path between each regular node (1-16 in Fig.4) and the dummy vertex D. To solve this problem, we use vertex D as source node in Dijkstra's shortest path (SP) algorithm and calculate the shortest distance from D as the source. Note that in our case there was no need to reverse the edges as they are bidirectional.

Inspired by the concept of constrained based routing (CBR) in Multi-Protocol Label Switching (MPLS) Traffic Engineering (TE), we impose minimum safety constraints on each link. This constraint aims to discard any link that is associated with a risk index of value 1 (very high risk) in the reported T, CO, HCN or D levels. A link that does not meet the minimum safety constraint is ignored (pruned) prior to applying the shortest path algorithm. This ensures that the evacuation algorithm will avoid perilous hallway sections.

There might be extreme cases where pruning can lead to a situation where the graph is no longer connected. In this case, when there is no route between a regular node and an exit node, our Constrained Shortest Path (CSP) algorithm will reinstate the pruned link and recomputes the shortest path regardless of the risk state. The constrained shortest path algorithm is described below:

CSP Algorithm

Input: Graph G'(*N'*, *E'*) with weights $W_t(i,j)$

1: Pruning: Ignore links that do not meet safety constraints. Check connectivity

2: Set vertex D as source vertex

3: Apply Dijkstra's algorithm

4: Find shortest distance from vertex D as source vertex

5: Output shortest path from each regular node to closest exit node

The above CSP algorithm is a core element (step 3 below) of our evacuation algorithm:

Evacuation algorithm

Input: Graph G'(*N'*, *E'*)

1: Collect sensor data from network server

2: Compute edge cost $W_t(i,j)$ for each edge

3: Apply **CSP Algorithm**

4: If (new routes are found) then

Push new directions to smart panels

end if

5: Wait for Δt seconds

6: Go to **1**

The time complexity of the proposed evacuation algorithm is influenced by two main factors: The collection of the sensor data and the execution of the CSP algorithm. The complexity of the latter is mainly driven by the execution of Dijkstra SP algorithm. When implemented with a min-priority queue, the time complexity of the SP algorithm comes down to Θ ((|N'| +|E'|). log |N'|). It can also be implemented in Θ ($|N'|^2$) using arrays.

3.4. Evacuation route computation process

When a fire hazard is detected, the central server sends commands to all sensor nodes to increase their reporting frequency above the running frequency of the dynamic evacuation algorithm. This ensures that each time the evacuation algorithm reruns, it receives up-to-date sensor data. The application server has a global view of the topology of the graph, such as the one illustrated in Fig.2. It gathers real-time information from the sensor nodes (via the central server), computes the edge weights $W_t^X(i,j)$, executes the evacuation algorithm, described above, and communicates with the smart digital panels to activate the proper evacuation arrow directions. As our evacuation algorithm runs every Δt seconds, when congestion builds up along a given pathway (a link between two nodes) as a result of the evacuation of many people along it, subsequent runs of the shortest path algorithm tend to circumvent this link as the weight associated with it increases. This indirectly contributes to balancing the flow of evacuees along the corridors, hence contributing to reducing the potential accidents that could occur when people stumble along overcrowded areas. In fact. A salient feature of our evacuation algorithm resides in its capability to assign multiple routes to groups of evacuators within the same pathway as new routes can be re-calculated after each iteration. This method has the potential to outperform single-route approaches in terms of safety at the expense of additional computational overhead.

3.5. Validation

To validate our proposed evacuation system, we opted for two simulation tools [42]:

- The *Fire Dynamic Simulator* (FDS) which is a computational fluid dynamics (CFD) model of fire-driven fluid flow used to simulate the spreading of fire inside the exhibition center.
- The *Evac* simulator which is the evacuation simulation module for Fire Dynamics Simulator (FDS), used to simulate the movement of people in evacuation situations.

We also make use of *Smokeview* (SMV) which is a visualization program that is used to display the output of FDS. Additional information, including source code, can be found at the NIST FDS and Smokeview webpage [43].

We are currently working on completing the simulation experiments and this ongoing work will be the subject of another research paper.

4. Conclusion and future work

In this contribution, we have proposed a dynamic crowd evacuation system for a multi-exit exhibition center. Our proposed system consists of several sensor nodes that collect real-time information about congestion levels, temperature, and toxic emissions along each leg of the escape routes. Based on this information, a centralized application server runs periodically a dynamic constrained shortest path algorithm to guide evacuees towards the safest exit, while minimizing the evacuation time. This guidance is dynamically conveyed to the evacuees via smart digital panels that are installed at major junctions.

Among the limitations of the proposed solution is the reliance on a centralized server for the computation of the safest routes, which represents a single point of failure. Further, existing crowd evacuation simulation models are not easy to customize, and they do not fully address the microscopic aspects of individual behavior such as the cognitive process in human behavior when trying to escape from dangerous situations [44].

The proposed approach is practical and offers a base framework for future research. Besides completing the simulation experiments, this work can be further explored in many directions:

First, we can investigate ways to further refine the definition of the weights associated with each link as well as the instruments that will be used to collect the associated parameters. For instance, the usage of video image captures to estimate the number of evacuees or to assess the hazard associated with each segment in the evacuation route is a research direction that is worth pursuing.

Future work can also look to add other fire risk factors such as smoke optical density (and particulate concentration) and visibility distance.

Future research can investigate other important considerations in the evacuation planning, such as the width of the exit doors, and the presence of people with special needs.

Extending the approach to handle more complex layouts including multi-floors scenarios can also be envisaged in future.

Another research extension to the present work is related to experimenting with other simulation tools such as SAFEgress [45] for the purpose of comparison.

Our approach is mainly based on a rule-based model and hence it would be interesting to consider fuzzy models to account for the inherent uncertainty that characterizes crowd evacuations.

Finally, for better efficiency, scalability, and robustness, we can consider migrating the processing of the collected IoT data from the current centralized server architecture towards a distributed set of edge nodes [46].

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