A Distributed Decision Support System for Building Evacuation

Avgoustinos Filippoupolitis and Erol Gelenbe

Abstract— **The evacuation of a building is a challenging problem, since the evacuees most of the times do not know or do not follow the optimal evacuation route. Especially during an ongoing hazard present in the building, finding the best evacuation route becomes harder as the conditions along the paths change in the course of the evacuation procedure. In this paper we propose a distributed system that will compute the best evacuation routes in real-time, while a hazard is spreading inside the building. The system is composed of a network of decision nodes and sensor nodes, positioned in specific locations inside the building. The recommendations of the decision nodes are computed in a distributed manner, at each of the decision nodes, which then communicate them to evacuees or rescue personnel located in their vicinity. We evaluate our proposed system in various emergency scenarios, using a multi-agent simulation platform for Building Evacuation. Our results indicate that the presence of the system improves the outcome of the evacuation with respect to the evacuation time and the injury level of the evacuees.**

I. INTRODUCTION

Decision making during an emergency response procedure has to be made in a timely manner in order to minimise the evacuation time and avoid injuries related with the ongoing hazard. It is, however, very difficult for the evacuees to make the best decisions during an evacuation. Most of the times they do not know which is the best path that they should follow in order to reach an exit since they are unfamiliar with the overall architectural design of the building. Moreover, the conditions inside the building may change due to the presence of a hazard that is spreading [1], such as a fire or a hazardous gas. This renders the task of finding a safe route to an exit even more difficult. A decision support system that provides directions to the evacuees during an emergency situation would prove beneficial to the overall outcome of the evacuation, since it could suggest the best available paths at any given time, avoiding the exposure of evacuees to unnecessary risk.

There are various approaches regarding the problem of decision support for emergency situations. In [2] the authors propose a system based on wireless sensor nodes, that can navigate a robot or a human towards an exit by avoiding the hazardous areas. Their approach, however, assumes a static hazard and there is no evaluation for a simulation scenario that includes evacuees who use the proposed system. A similar system is prosposed in [3], which uses a sensor network in order to calculate a path that leads to an exit and does not pass through the hazardous area. The authors demonstrate the ability of the algorithm to find the safest paths, but do not consider a spreading hazard nor evaluate their approach in a simulation scenario that involves evacuees.

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Our approach focuses on the design and evaluation of a decision support system that can be used during an emergency situation inside a building. The system must be able to function in real-time, adapt to the changes of the environment and provide reliable suggestions to the evacuees regarding the direction of the best available exit. This approach has been inspired by [4] where vehicles, modelled as smart agents, are traversing a dangerous urban grid. The agents, who use information coming from the environment and from other agents, are able to adapt in order to travel rapidly and safely. Our system operates in a building environment, where civilians are taking part in an evacuation in the presence of a spreading hazard. By following the directions provided by the decision support system, they can evacuate the building using the best available paths and avoiding the hazardous areas. We evaluate the prosposed system by the use of a multi-agent Building Evacuation Simulator which models the evacuation procedure. This approach provides a realistic environment in which our proposed method can be tested.

The rest of the paper is organised as follows: Section II gives the details of the modelling approach we followed for the design of the system. In Section III we present the distributed algorithm that is used by the decision support system , while the evaluation of the system along with simulation results for various scenarios is the subject of Section IV. Finally in Section V we present our conclusions and describe our future work.

II. DESCRIPTION OF THE SYSTEM

We begin by giving the design details of the decision support system. We present the assumptions we made and the modelling approach we adopted.

A. Assumptions

Our first assumption is that the layout of the building is known. This is valid for the case of a decision support system that has been pre-installed in the building before the evacuation process is initiated. Since such a system will be part of a building's safety infrastructure, it must have already been deployed when the emergency situation occurs.

Another assumption is the existence of a number of Decision Nodes (DN), installed in specific locations inside the building. These devices do not need to have high processing power or storage. Their job is to compute the direction that should be followed by each evacuee, towards the best

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available exit. The advice of a DN is communicated to people in its vicinity. The interaction between the evacuees and the DNs can be accomplished by the use of a visual indicator (such as a smart panel) or by a wireless communication device (i.e. a PDA) which is carried by the evacuees or the emergency personnel and receives the suggestions from the DNs.

Finally, we assume the existence of a network of sensor nodes, that provides the Decision Nodes with real-time information about the conditions inside the building. This information can be related to the temperature of a location or the presence of smoke.

B. Graph Representation of the Building

We have used the known building layout to construct a graph G. Figure 1 shows the floor of a building and the corresponding graph. The vertices of the graph correspond to locations where people can congregate (e.g. rooms, corridors, doorways or hallways). A link between two vertices of the graph represents a path that can be followed by the evacuees.

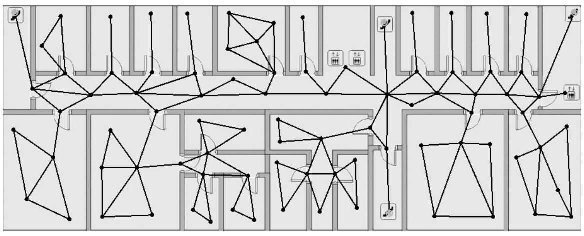


Fig. 1. A graph corresponding to one floor of a building

The length $l(i,j)$ of a link between two vertices represents its physical distance. Each sensor is associated with each link (i,j) and monitors its hazard intensity $H(i,j)$. Under normal conditions (when there is no hazard present) $H(i,j) = 1$. The value of $H(i,j)$ will increase with the observed hazard.

In order to obtain a metric that expresses how hazardous a link is, we introduce the idea of "effective length". We define the effective length $L(i,j)$ of a link as:

$$L(i,j) = l(i,j) \cdot H(i,j) \tag{1}$$

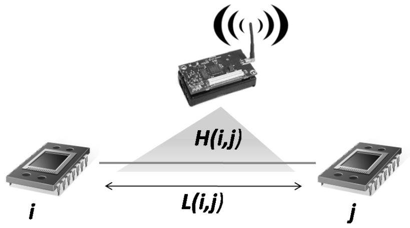


Fig. 2. A sensor that monitors hazard intensity on a link between two Decision Nodes

As we can see from Equation 1, the value of L depends both on the physical length of a link and on the value of the hazard along that link. When there is no hazard present, we have $L \equiv l$, since the effective length is equivalent to the physical length of the link. The higher the value of L on a link, the more hazardous it is for a civilian to move along it. Figure 2 illustrates the use of sensor nodes for determining the value of the effective length..

Figure 3 depicts an example topology where Decision Nodes and sensor nodes are positioned in specific locations inside a room of a building. Each DN is placed at each of the vertices of the graph G. In practice, however, there could be fewer decision nodes than vertices in G, with each DN being in charge of providing decisions for a set of contiguous locations of G.

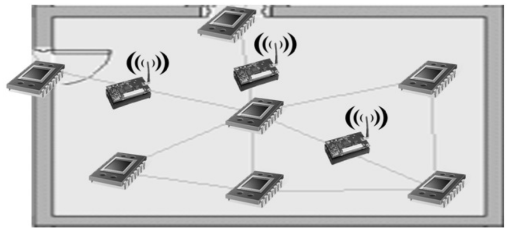


Fig. 3. Decision Nodes and Sensors Nodes Positioned in specific building locations

III. A DISTRIBUTED ALGORITHM FOR DECISION SUPPORT

Instead of using a centralised system to compute the value of the effective length of the paths to an exit, we propose a distributed architecture. We explain the advantages [5] of this approach and give the details of the distributed algorithm used by each decision node.

A. Advantages of a Distributed Approach

The proposed decision support system could be implemented in a centralised manner. In that case, the algorithm runs in one central processing centre. The centre is responsible for gathering information from the sensor nodes, executing the algorithm and communicating the resulting decisions to the respective decision nodes. This approach, however, has numerous drawbacks that have a negative impact on the functionality of the system and can impair the result of an evacuation procedure.

A centralised approach is not fault tolerant, since it relies on a single point of data collection, processing and retransmission. In the case of a failure in the processing centre, the decision system cannot function. Furthermore, there may also be failures in the overall communication system during an emergency. Using local communications to inform evacuees using the Decision Nodes is more robust compared to a centralised solution which relies on being always able to communicate with the processing centre.

Moreover, the computational requirements for a large scale system may not be met by a single processing centre. As the size of the building and the number of floors increases, the required number of decision nodes increases accordingly. This has a direct impact on the amount of information that has to be processed by the centre, in order to compute the best path towards the exit. In our distributed system, each Decision Node executes the decision support algorithm locally and relies only on its own computational resources. Thus, the size of the system does not affect the size of data that have to be processed.

A distributed approach also facilitates an extensible and scalable design process. In other words, the design principles of the distributed system for a given size of building can be scaled up or down, to address larger or smaller buildings using the same principles and building blocks.

B. Description of the Distributed Algorithm

The algorithm that we propose is inspired by the distributed shortest path problem [6], [7], [8] and from adaptive routing techniques such as Cognitive Packet Networks [9]. It is executed by each Decision Node, in a distributed manner, and its output is the next Decision Node that is on the best available path towards an exit.

A Decision Node, at vertex u, stores the following information:

- The effective length L of all the links that are incident to u
- For every neighbour n of u, the effective length of the path y from n to an exit e : $L(n, e, y)$
- The effective length of the shortest path x , from u to an exit e: $L(u, e, x)$
- The next suggested Decision Node

The initial conditions for the algorithm are set as follows:

$$L(u,e,x) = \begin{cases} 0 & \text{, if } u \in E \\ \infty & \text{, otherwise} \end{cases} \quad (2)$$

where E is the set of available building exits.

Since the decision support system is already installed in the building when the hazard starts spreading, we can consider that the initial condition for each Decision Node,at that time, is the actual physical length $l(u, e, x)$ of the shortest path from a decision node u to an exit e. This is a consequence of the fact that the system will be already operating before the hazard occurs, thus each Decision Node will have selected a path that minimises the effective length when no hazard is present.

We should also point out that it is not necessary for a Decision Node to keep information regarding the effective length L of the paths towards all the available exits. As the algorithm is executed, this information is propagated from all the exits to all the Decision Nodes. Each Decision Node will eventually select the exit that minimises the value of the selected metric, which in our case is the effective length of the path from the node to the exit. The selection of an exit depends on the location of the Decision Node, the locations of the exits and the spreading of the hazard.

When the Decision Support system is in operation, each Decision Node at u periodically executes Algorithm 1 and provides a suggestion to the evacuees that are in its vicinity. The suggestion is of the form **"go to v"**. Communication and computation is much faster than the movement of individuals. Since conditions will change rapidly (e.g. the spread of fire), the Decision Nodes will periodically execute the algorithm, update the distance information and communicate the most recent valid advice to neighbouring evacuees or other active entities such as firemen or rescue personnel.

Algorithm 1 Distributed calculation for the effective length $L(u, e, x)$

> **Send** to every neighbour n of u, the effective length of the path from u to the exit e : $L(u, e, x)$
> **for** each sensor node monitoring a link incident to u **do**
>   **Request** hazard intensity H from sensor node
>   **Calculate** the effective lengths $L(u, n)$,where n is a neighbour of u
> **end for**
> **Update** the effective length $L(u, e, x)$ of the shortest path x to the exit:
> $L(u, e, x)$ = min $\{L(u, n)$+$L(n, e, y)$: $\forall$ neighbours n of u, $x = ny\}$
> **Set** the next suggested Decision Node v:
> v = argmin $\{L(u, n)$ + $L(n, e, y)$: $\forall$ neighbours n of u, $x = ny\}$

IV. Evaluation of the Decision Support System

We evaluate our proposed Decision Support system inside a Building Evacuation Simulator we have developed. A description of the simulator and its characteristics is firstly presented, followed by simulation results of evacuation procedures that use our system.

A. The Building Evacuation Simulator

We have implemented the proposed decision support system inside the Building Evacuation Simulator (BES) [10], [11], in order to evaluate its performance during an emergency situation inside a building. The BES is an agent-based simulator for building evacuation. The actors that take part in the simulation are modeled as agents. Each one has its own health model and movement model that depend on the individual characteristics of the actors and on the environment. The implementation of the agents was done using the JADE framework [12]. The physical world of a building is viewed as a collection of "Points of Interest" (PoI) and available links between them, which form a directed graph. Each PoI is assigned to a group according to its location, for example, a room or section of a corridor. The links represent the walking access between adjacent PoI. The BES also simulates congestion and the spread of a hazard inside the building [13], [14] (such as fire or hazardous gas). The main reasons for choosing to evaluate the decision system using the BES are:

- **Realism:** The BES is composed of actors that move and interact inside the simulated world, while the environment is changing due to the spreading hazard. Different types of actors, such as civilians, rescuers and medical personnel, can participate in the simulation while the decision support system is used to provide them with directions regarding the best available exit route. Thus, we can investigate the efficiency of our system under realistic conditions and evaluate its performance by analysing the outcome of numerous simulated scenarios.

- **World Model Structure:** The decision support system we prospose is based on a graph, which is similar to the one used by the BES. This structural homogeneity was beneficial to the integration of the decision support system with the BES. We were able to develop the decision model without the need for major modifications in the organisation of the simulator, which would have resulted in unnecessary complexity and difficulty.
- **Extensibility:** The modular, agent-based structure of the BES allowed for a relatively straightforward addition of the entities that are part of the decision support system, such as Decision Nodes and sensors. This contributed to the rapid development and implementation of the decision support system.

B. Evacuee - System Interaction

The evacuation scenarios in which our proposed system is used, involve a multi-storey building and a hazard spreading inside it. Civilians are located inside each floor of the building. When the simulation begins, each civilian tries to evacuate and starts moving towards an exit.

In the case where the decision support system is used, each civilian decides its next destination based on the recommendation of the respective Decision Node. Figure 4 illustrates the floor of a building, as it is represented through the BES interface. We can also note the presence of a fire, which is spreading inside the floor. The arrows represent the directions that an evacuee receives from a Decision Node which is located in its vicinity. The interaction between an evacuee and a Decision Node can be accomplished by either a visual indicator (such as a smart panel) or a wireless communication device (such as a PDA) which is carried by the evacuees and is able to to receive the directions from the Decision Nodes. Each Decision Node directs the evacuees towards one of its neighbouring Decision Nodes, along the best path that leads to the exit and avoids exposure to the hazard.

Finally, the movement of the evacuees in the absence of the system is modelled using an optimistic approach, since each evacuee is assumed to have a full knowledge of the building's structure before the hazard starts spreading. We consider that the evacuees are familiar with all the available exits and are able to follow the shortest paths that lead to them. In terms of modelling, this is translated in a full knowledge of the building graph and a calculation of the shortest paths by using Dijkstra's algorithm. An evacuee becomes aware of a hazardous area when it reaches a location close to it. This triggers an update in its knowledge of the building graph and a re-calculation of the shortest path.

C. Experimental Setting

In order to evaluate the proposed system in a wide range of conditions, we have chosen to randomise the following scenario parameters:

- **Initial civilian locations:** For each simulation run, the initial locations of the civilians are chosen from a uniform distribution over the graph vertices of a floor. This allows as to test our decision system's performance under different building occupancy patterns, including cases where civilians are located near the hazard when it starts spreading.
- **Hazard spreading:** The spreading rate of the hazard also differs between consecutive simulation runs. It is based on the probabilistic hazard model used by the Building Evacuation Simulator [10], [13]. This increases the realism of the simulation, since it guarantees that the spreading of the hazard will not be identical for all the simulation scenarios.

D. Simulation Results

We evaluated the proposed decision support system using the following metrics:

- Percentage of evacuees that have exited the building versus the evacuation time. This metric reflects the efficiency of the system in directing the civilians towards the exits, with respect to the speed of the evacuation procedure. The higher the slope of a curve, the faster the evacuees exit the building.
- Average remaining health of the evacuees. It denotes the degree of exposure to the hazard. A low value indicates that the system has succeeded in directing the evacuees along safe paths, avoiding the hazardous locations.
- Percentage of fatally injured evacuees. This is a straightforward metric and it denotes the number of evacuees that were not able to exit the building due to excessive exposure to the ongoing hazard.

We have evaluated different cases were the decision system is used, by executing two hundred simulation runs for each case. The difference between them is how frequently each Decision Node executes the algorithm. This will affect the speed of propagation of information among the decision nodes and the adaptivity of the system to the dynamic environment. We have also included a case where there is no decision support system in the building.

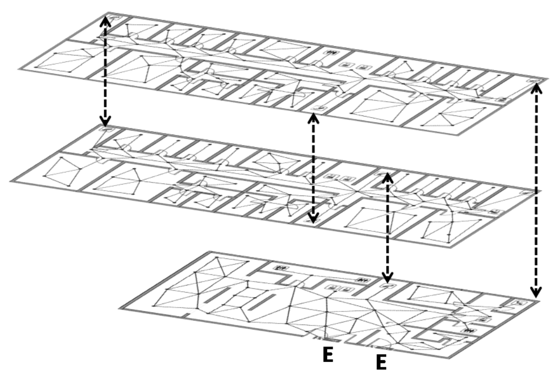


Fig. 5. The building used in the first and the second evacuation scenarios

1) Scenario 1: The *first evacuation scenario* involves the three storey building illustrated in Figure 5. The dashed

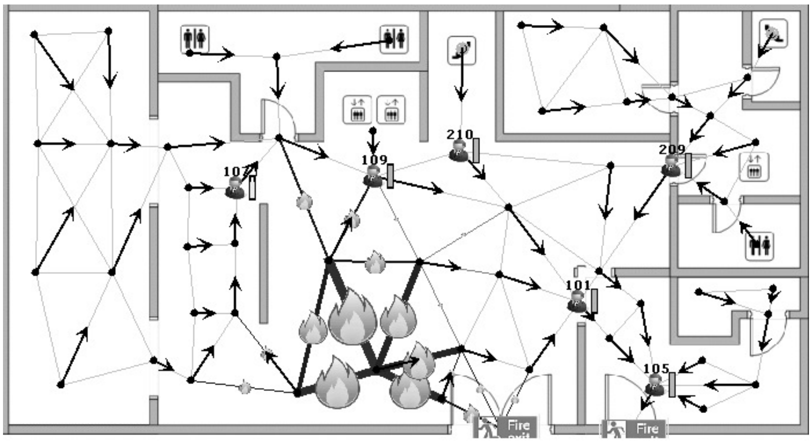


Fig. 4. The decision support system inside the BES. The arrows correspond to directions from the Decision Nodes

arrows represent the staircases along which the evacuees can move from one floor to another. The building occupancy level is 30 civilians in total (ten civilians per floor) and there are two exits located on the ground floor. A fire starts on the ground floor of the building. Figure 6 illustrates the percentage of evacuees that have excited the building , versus the evacuation time. We notice that in the cases where the decision support system is used, the evacuation procedure finishes faster and with a higher percentage of civilians exiting the building.

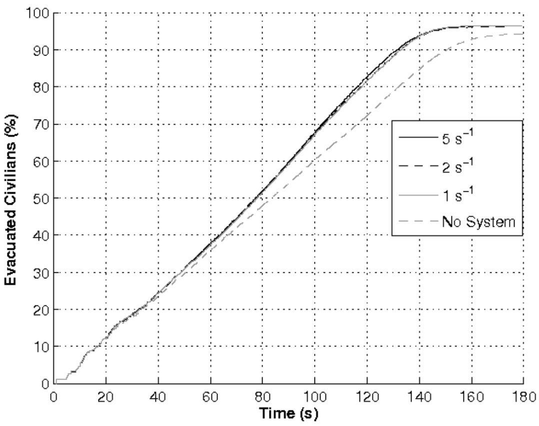


Fig. 6. Percentage of evacuees that have exited the building vs. Evacuation Time, for different algorithm execution frequencies

The evacuation results in terms of average remaining evacuee health are shown in Figure 7. The decision support system guides the evacuees towards the exit by avoiding the hazardous areas, achieving superior results compared to the case were no system is present.

Figure 8, illustrates the percentage of fatally injured evacuees. In this case also, the decision support system performs better compared to the case were the evacuees try to exit the building on their own, a result that confirms that the existence of the system improves the outcome of the evacuation procedure.

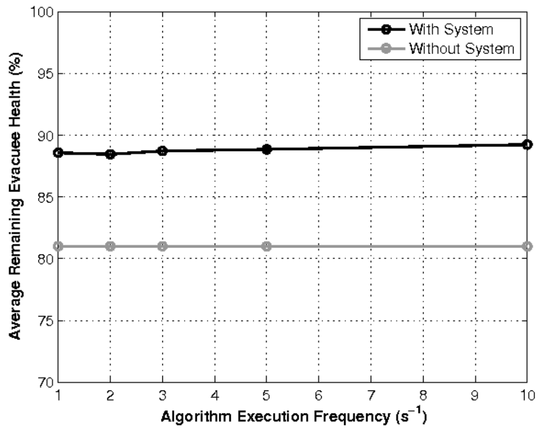


Fig. 7. Mean remaining evacuee health vs. algorithm execution frequency

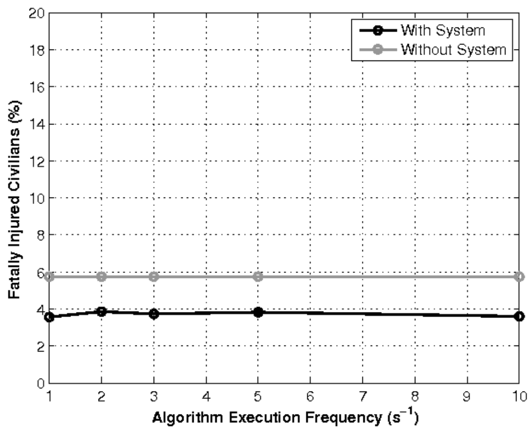


Fig. 8. Mean percentage of fatally injured evacuees vs. algorithm execution frequency

2) *Scenario 2:* In the *second evacuation scenario* we consider again the building depicted in Figure 5. This time the initial location of the fire is different, compared to Scenario 1; the fire starts in the second floor of the building. The exit of the building is located on the ground floor. We have run two sets of simulation runs, each one with a different level of building occupancy. In the first set we have assumed a total of thirty civilians inside the building (ten civilians per floor), while in the second set we considered twenty civilians per floor. Figure 9 illustrates the percentage of evacuees that have excited the building , versus the evacuation time. We can note that the outcome of all three cases where the decision system is present is better compared to the case where the system is absent. We can verify this by comparing the slope and the height of the respective curves: The decision support system achieves a faster evacuation and a higher percentage of safely evacuated civilians. We observe that the higher occupancy level of the building affects the total time of the evacuation, as it takes longer for the civilians to exit the building due to the increased congestion. However, as it can be verified by Figure 9(b), the use of the decision support system still results in a faster and safer evacuation. The average remaining health of the evacuees is shown in Figure 10, for the two different building occupancy levels. It is now more clear that the presence of the decision support system directs the evacuees away from hazardous areas and towards the best available exit. We notice that when the occupancy level of the building increases, the absence of the decision support system results in an even lower average remaining health. This is explained by the fact that the congestion level is now higher and the evacuees need more time to move inside the building. Thus, the hazard spreads in more areas and the probability of being exposed to it increases. Figure 11 shows the percentage of fatally injured evacuees. We can again verify that the use of the decision support system results in minimal casualties during the emergency situation and that in every case it provides better results compared to the case where the system is not present.

3) *Scenario 3:* Finally, in order to test the effectiveness of our proposed system in a different building structure, the *third evacuation scenario* takes place inside the building illustraded in Figure 12. The staircases are represented by the dashed arrows. The occupancy of the building is sixty civilians (20 civilians per floor) and there are four exits located on the ground floor. The initial location of the fire is on the ground floor. We can still verify that the decision support system improves the outcome of the evacuation. Figure 13 shows that the outcome of the evacuation procedures where the system is used is better compared to the case where the system is absent. The average remaining health of the evacuees is higher when they follow the directions of the system, as we can verify from Figure 14, while the use of the system also results in fewer fatalities as Figure 15 illustrates.

4) *The Effect of the Algorithm Execution Frequency:* As we can see from Figures 9 to 11 , the execution frequency of the distributed algorithm by the decision nodes affects the performance of the system. This is due the fact that

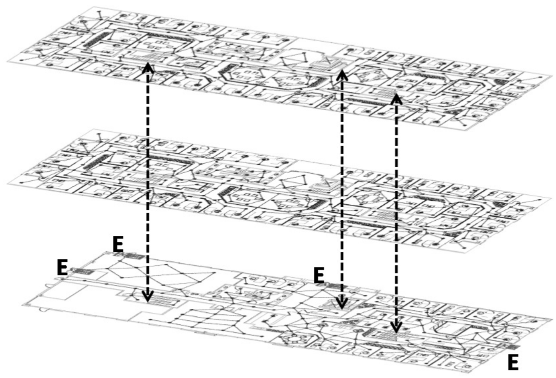


Fig. 12. The building used in the third evacuation scenario

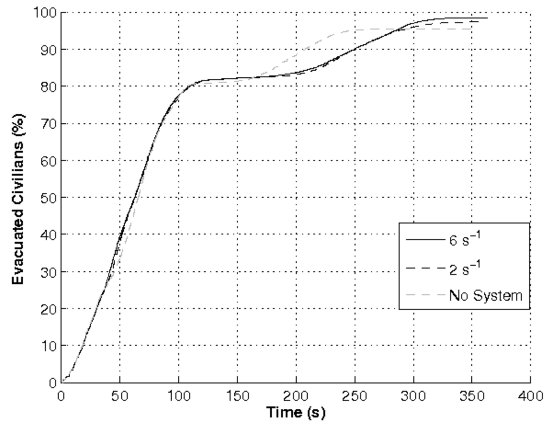


Fig. 13. Percentage of evacuees that have exited the building vs. Evacuation Time, for different algorithm execution frequencies

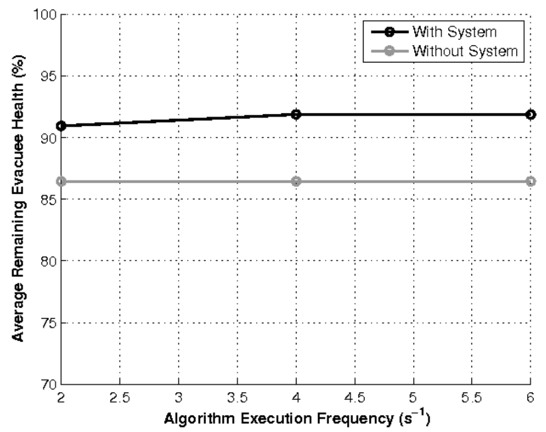
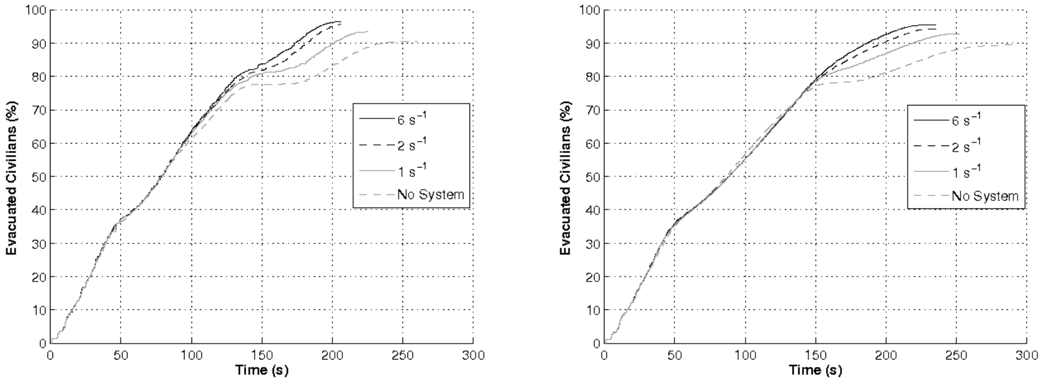
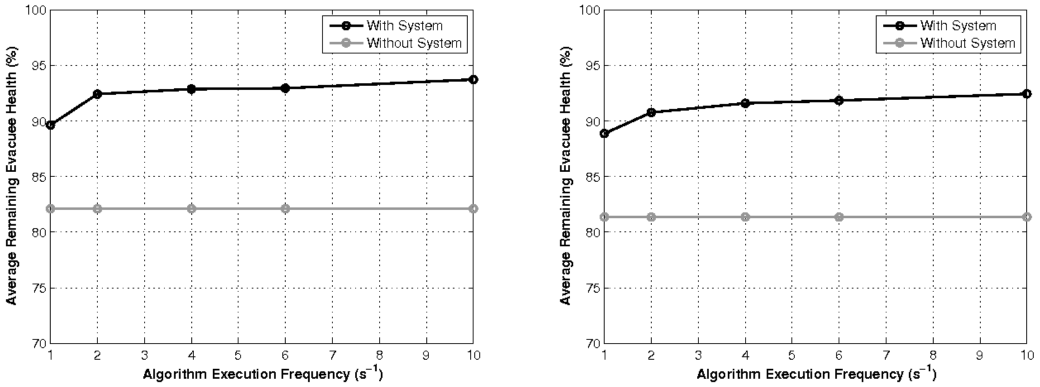


Fig. 14. Mean remaining evacuee health vs. algorithm execution frequency



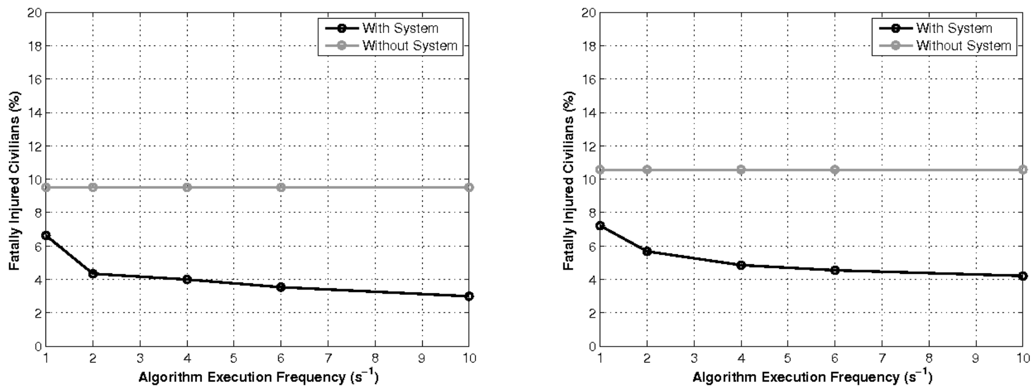
(a) (b)

Fig. 9. Percentage of evacuees that have exited the building vs. evacuation time, for different building occupancy levels: 10 civilians per floor (a) and 20 civilians per floor (b), and different algorithm execution frequencies



(a) (b)

Fig. 10. Mean remaining evacuee health vs. algorithm execution frequency, for different building occupancy levels: 10 civilians per floor (a) and 20 civilians per floor (b)



(a) (b)

Fig. 11. Mean percentage of fatally injured evacuees vs. algorithm execution frequency, for different building occupancy levels: 10 civilians per floor (a) and 20 civilians per floor (b)

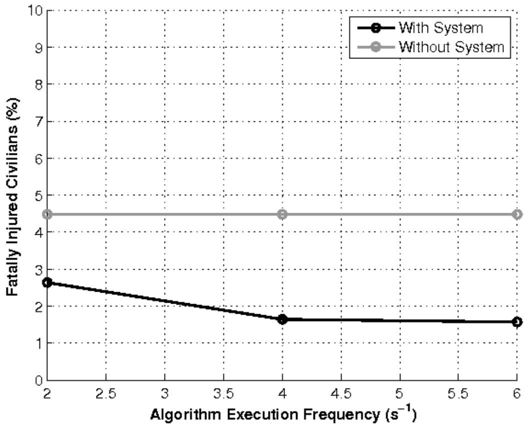


Fig. 15. Mean percentage of fatally injured evacuees vs. algorithm execution frequency

the propagation of the changes in the environment (e.g. the change on the measurement of a sensor node) depend on the execution frequency. A high value for the algorithm execution frequency results in a more adaptive system which is able to give fast, correct suggestions to the evacuees. This however comes at a cost of message transmissions. On the other hand, lower execution frequencies result in inferior performance. This is clearly depicted in Figure 9 where the percentage of evacuated civilians decreases along with the algorithm execution frequency. Finally, we should note that in the case of Scenario 1, where the location of the hazard is close to the exit, the algorithm execution frequency plays a minor role in the success of the evacuation procedure. This can be verified by Figure 6.

V. Conclusions and Future Work

We have presented a decision support system that aims at providing directions to evacuees during an emergency situation. The system consists of Decision Nodes, positioned in specific locations inside the building, and sensor nodes that provide information regarding the intensity of the spreading hazard. Each decision node computes the best direction towards the exit in a distributed manner, using only local information. The directions of the Decision Nodes are communicated to the evacuees via Smart Panel Indicators or Wireless Devices that they carry. The proposed system is evaluated using a multi-agent Building Evacuation Simulator that we have developed. The actors taking part in the simulation follow the directions of the decision support system as they move inside the building. Our study includes simulation scenarios for multiple floors, different buildings and various building occupancy levels. The simulation results illustrate that the presence of the decision support system improves the outcome of the evacuation procedure by directing the evacuees towards safe paths, which avoid the spreading hazard and minimise the evacuation time and injuries.

In future work, we will investigate new definitions for the effective length of a link. We will take into account parameters inherent to emergency response so as to lead civilians away from congested and potentially hazardous areas responding to dynamic changes inside the building. Thus, the decision support system will deal with congestion along civilian paths and prediction of the hazard propagation. Furthermore, we will extend our evaluation in the case where input from a real wireless sensor network is used during the evacuation procedure. The evaluation of our system in this setting will allow as to study the effect of network issues, such as delays and packet loss, on the performance of the distributed decision support system.

VI. Acknowledgements

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