Agent-Based Simulation of Spatial Cognition and Wayfinding in Building Fire Emergency Evacuation

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Abstract. There is a need to understand how people and environment react in a fire building emergency. Sometimes in the wayfinding process decision errors may occur mainly based on topological errors of the signage. A situation is critical if a decision about which path to take cannot be made with certainty, especially in a crisis situation. An agent-based simulation of human's behavior in escaping from the fire with due attention to the building's signage and dynamic nature of fire propagation affecting the wayfinding task is outlined in this paper. The hypothesis of the paper is that successful navigation is possible if the agent is able to make the correct decision through well-defined cues in critical cases, so the design of the building signage is evaluated through the agent-based simulation. Construction of mental representations of spatial environment and exploring models in the agent-based simulation have been proposed and a computational model successfully tested in an indoor complex hospital environment in different situations and the evacuation time from the building is computed. The most appropriate signage design resulted in the shortest evacuation time in various situations.

Keywords: Spatial Cognition, Agent-based Simulation, Emergency Management, Wayfinding

1 Introduction

One of the most disastrous forms of collective human behavior is the kind of crowd stampede induced by panic, often leading to fatalities as people are crushed or trampled. Sometimes this behavior is triggered in life-threatening situations such as fires in crowded buildings. Although engineers are finding ways to alleviate the scale of such disasters, their frequency seems to be increasing with the number and size of mass events. An example of such topics which has been considered in this paper, is fire building evacuation modeling. The ability to enable efficient circulation of people in heavily populated enclosures is important to the day to day operation of large complex buildings. More importantly, it is an essential design feature in the event of emergency situations. The aim of this research is to support people's wayfinding and escaping process using optimum quality and placement of building signage which helps them finding the exits in a safer way.

As architects continue to implement novel concepts in building design, they are increasingly finding that the fixed criteria of the traditional methods of prescriptive building codes are too restrictive. This is due in part to their almost total reliance on configurational considerations such as travel-distance and exit width. Furthermore, as these traditional prescriptive methods are insensitive to human behavior or likely fire scenarios, it is unclear if they indeed offer the optimal solution in terms of evacuation efficiency.

The emergence of performance based building codes together with computer based evacuation models offer the potential of overcoming these shortfalls and addressing the needs not only of the designers but also the legislators. However, if such models are to make a useful contribution they must address the configurational, environmental, behavioral and procedural aspects of the evacuation process. The result is that the fire safety engineer is empowered to realize the full value of mathematical models to help in the prediction of human behavior during evacuation, and to determine the consequences of fire under a variety of conditions. This in turn enables them to design and implement safety measures which can potentially control, or at least reduce the impact of fire.

Intelligent approaches for modeling fire safety evacuations is a useful new method to evaluate capability of such methods. In this paper we report of an agent-based simulation of escaping from the fire building and computed the total evacuation time for various building signage design and compared the results and found the optimum placement and design of the building informational cues. This agent-based modeling uses concepts from cognitive science and wayfinding research. Cognitive research will lead to improved systems that take advantage of an understanding of human's geo-spatial perception and conception, including that of geo-spatial experts. A geo-spatial information technology that is more responsive to human factors in its design will greatly improve the effectiveness and efficiency of spatial decision-making. This includes both general concerns about the limited geo-spatial knowledge in the population and more general concerns, such as environmental change.

A common task of humans is to navigate from one place to another, often in an unknown or critical area. Typically, maps are used for navigation. Maps may not be available or their use may not be possible due to the critical situations. Recent research on human wayfinding has a balanced focus on mental representations and processes of wayfinding [15]. The goal-driven reasoning chain that leads to action begins with incomplete and imprecise knowledge derived from imperfect observations of space [15].

Actions result in further observations, derived knowledge and further actions, until the goal is achieved or the wayfinder gives up. A special case of wayfinding in a complex building, that is finding exit ways in a fire emergency, is the application of the model.

The goal of the previous work of the agent-based simulation of human behavior was to develop a computational theory of perceptual wayfinding [16]. That theory uses an agent-based approach and can just explain people's wayfinding behavior in unfamiliar buildings. It is different from previous computational models for wayfinding, which were built to investigate how mental representations are created, stored and used. These models assume that people become familiar with their environments over time and, therefore, acquire cognitive maps [5, 12].

Artificial intelligence (AI) researchers in computer science and other disciplines have developed simulations of spatial intelligence, in some cases as part of the design of mobile robots [22]. In this research we have mainly focused on agent-based simulations for optimum designing of the building signage system in order to simplify the task of wayfinding in an unknown complex building during fire emergency. To represent and simulate people's processes of spatial cognition and wayfinding, it is necessary to understand how people immediately make sense of spatial situations while performing a wayfinding task which will occur in a building during fire emergencies. Some of the assumptions for rescue operation in these situations may fail and so we should use intelligent approaches in these contexts.

2 Background

Several recent events have motivated discussions on how to best protect and safely evacuate building occupants during fire emergencies [13]. In this modelling, we should not neglect the different behaviors of human beings in crisis situations. Spatial cognition, occupant characteristics, human response to cues, decision-making and wayfinding in building fire emergency management have been discussed in this paper. Therefore, major concepts and scientific backgrounds for the agent-based modelling of spatial cognition and wayfinding in such a crisis situation have been introduced below.

2.1 Spatial Cognition

Research in the cognition of geo-spatial information deals with human perception, memory, reasoning and communication involving the spatio-temporal objects and events, both in the real world and in their digital representations. Basic research in geo-spatial cognition is relevant to many issues involving geo-spatial information such as data collection and storage, graphic representation and interface design, spatial analysis, interoperability, decision-making and the social context of GIS. We believe that many aspects of geo-spatial information system usability, efficiency and profitability can be improved by greater attention to cognitive research. It is claimed that our experience and interaction with the environment is based on the use of recursive and imaginative patterns.

Spatial cognition is composed of several elements including landmarks, route maps and survey maps. Landmarks are identifiable environmental markers associated with specific locations [4]. Route maps are sequences of instructions, often involving landmarks, which describe at a personal level how to get from one location to another [1]. Survey maps are similar to topological maps and describe the spatial layout of the environment as opposed to reflecting a specific navigational task [1]. Spatial cognition concerns the study of knowledge and spatial properties of objects and events in the world. Cognition is about knowledge: its acquisition, storage and retrieval, manipulation and use by humans and intelligent machines. Generally speaking, cognitive systems include sensing and perception, thinking, imagery, memory, learning, language, reasoning and problem solving. Spatial properties include location, size, distance, direction, separation and connection, shape, pattern and movement. Human spatial cognition is an interdisciplinary research area in cognitive science [16].

A widely accepted model of spatial learning suggests that spatial knowledge of places is developed in a sequence of three stages or elements. First is landmark knowledge, unique features or views that identify a place. Second is route knowledge, based on travel routines that connect ordered sequences of landmarks. The third stage is survey knowledge, knowledge of two-dimensional layouts that includes the simultaneous interrelations of locations.

2.2 Wayfinding

Wayfinding, getting from some origin to a destination, is one of the everyday problems that humans encounter [17]. It is a purposive, directed and motivated activity [6]. Human wayfinding research investigates how people find their ways in the physical world, what they need to find it, how they communicate directional information and how people's verbal and visual abilities influence wayfinding [14]. According to Lynch [11] wayfinding is based on "a consistent use and organization of definite sensory cues from the external environment". Wayfinding is a complex human activity involving moving along while evaluating alternatives and making decisions. It is defined as a spatial problem solving process with the three sub-processes including decision-making, decision execution and information processing [20].

Wayfinding typically requires planning and the ability to stay oriented while moving. Navigation is this coordinated and goal-directed travel through space. It consists of two components, locomotion and wayfinding. Locomotion refers to the guidance of oneself through space in response to local sensorimotor information in the immediate surrounding and includes such tasks as identifying surfaces of support, avoiding obstacles and moving toward visible landmarks. Locomotion generally occurs without the need for an internal model or cognitive map of the environment. Wayfinding refers to the planning and decision-making that allows one to reach a destination that is not in the immediate sensory field and includes such tasks as choosing efficient routes, scheduling destination sequences orienting to non-local features and interpreting verbal route directions.

Two fundamental processes are involved in orientation during navigation. The first process is the recognition of external features or landmarks. In some cases, the recognized landmark is the goal, but more commonly the landmark aids orientation by serving as a key to know the spatial relations stored in an internal cognitive or external cartographic map. The second process is updating a sense of orientation by integrating information about movement speed, direction and/or acceleration without reference to recognized features. There are four classes of environmental variables that influence wayfinding performance within built environments: visual access, architectural differentiation, signs and room numbers to provide identification or directional information and plan configuration [21]. Spatial knowledge is assumed to consist of landmark, route and survey (configurational) knowledge [19]. The following guidelines for good wayfinding signage are developed [2]:

- Wayfinding information should be given at the point that a decision needs to be made.
- Legibility is important. The information on the sign should be perceived with ease. Make sure signs are not hidden from view by bushes, trees, etc.
- Readability is the ease with which information can be understood. People glance for messages rather than read them word for word. Keep the messages short. Don't expect long messages to be read from moving cars.
- Reliability relates to the question of whether or not the signs give correct information. Signs with false information can lead to stress, frustration and mistrust.
- Accessibility, meaning that persons with disabilities can read and use the signs.

2.3 Intelligent Agent

The realistic representation of human behavior in crowd simulations requires rich models or architectures that are able to represent partly, the complex human behavior in fire emergencies. Modeling complicated human behavior for a general situation is extremely difficult and involves a certain degree of abstraction backed up by a rich architecture. One of the commonly used ways has been designing an intelligent agent that will mimic the overall (abstract) characteristics of a human.

Agent theory is a young scientific field without common paradigms. Different people from different domains working in the field have different understandings of the concepts. Agent-based simulation provides a new solution to the simulation of social processes, because it allows including representations of individuals with individual capabilities and preferences into the model. The core element of agent theory is the agent concept [3]. Due to the heterogeneity of the field, there is no common agreement about a definition of the term ‘agent’. Anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors can be an agent [18]. An agent is an entity that is capable of acting in its environment and capable of perceiving its environment (Figure 1). The environment provides percepts to the agent, which the agent perceives through its sensors [6]. Agents are environment dependent; once an agent leaves the environment to which it is adapted, it may no longer be considered as an agent.

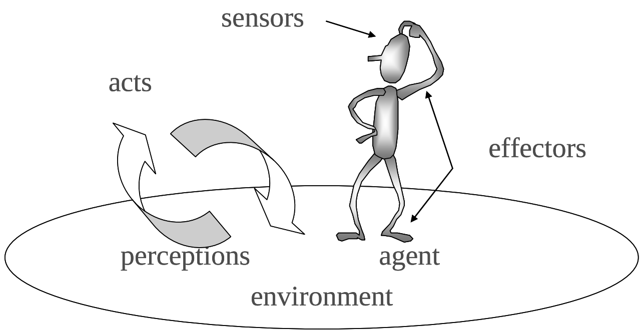

Fig. 1. An agent embedded into the environment [3]

Intelligent agents are autonomous and can be cooperative, learning and adapting and equipped with social abilities, reactivity and pro-activeness. The agent framework offers two advantages:

- The paradigm is based on folk psychology, where the core concepts of the paradigm map easily to the language people use to describe their reasoning and actions in everyday life.
- The paradigm is a relatively mature framework and has been successfully used in a number of medium to large scale software systems.

Agents, in general, differ in the way they interact with the environment (perceiving and acting), to what extent they know the environment (the built-in knowledge) and whether they can predict the changes in the environment or not. A perception system enables an agent to classify and distinguish the states of the environment and other agents. Some literature distinguishes between passive and active perception systems. In a passive perception system, the signals from the environment are processed and then segmented leading to identification of the elements of the environment or other agents and choosing the action. The wayfinding agent has an active perception system. Its active perception system links signals from the building environment with the goal and representation of the street network coming from the cognitive system of the agent. The agent links this information with the information about the environment which forms its initial belief. It links the observation of the reality with its internal cognitive system and learns about the environment. By learning the wayfinding environment, the agent updates its beliefs about the environment.

3 Methodology

The navigating human is viewed as an agent with state and performs actions such as perceiving information from the real world and moving through the environment. Given a sequence of landmarks between the current position and a desired destination, the agent executes the appropriate steps necessary to reach the destination point. Most of the wayfinding problems are due to the poor quality of the building signage or lack of them in some critical decision points. Therefore, designing signage is an important task which is done and analyzed successfully in this research in order to gain the most optimum design and placement of the building cues [7]. Figure 2 shows the agent's state at a decision point. As part of the agent's state, the actual planned path is marked as a directed graph with arrows.

Fig. 2. Decision taken at every decision-point [7]

An action is modelled as a physical displacement of the wayfinding agent. The agent moves in the building environment and changes its position in it. The wayfinding agent observes the situation in the real world and learns about the building environment. Learning occurs when its observations do not confirm its belief about the exit ways and their observable attributes. The wayfinding agent is an active learner, which means that it uses the learned information in its planning algorithm when it plans the traveling path. On the contrary, a passive learner simply tries to learn the utility of being in different states without actively using the learned information. Learning is called to be incremental if the agent tries to update its old hypothesis whenever a new example or information arrives [10]. Planning happens at every decision point where the agent has to select the next way to continue wayfinding via the optimal path to the destination. The agent's decision is based on the plan; it takes the path suggested by the planning program as the first step on the planned path to the destination.

The agent would gain information from the building's signage which may be either directional or textual. By due attention to the cues and dynamic propagation of fire and smoke on the agent's interface, it would gain some information about its situation in the environment and its state would change. Formalizing the conceptual model for the cognizing agent allows describing it more precisely than by using a verbal description and to create a practical tool for simulating the test case (Figure 3).

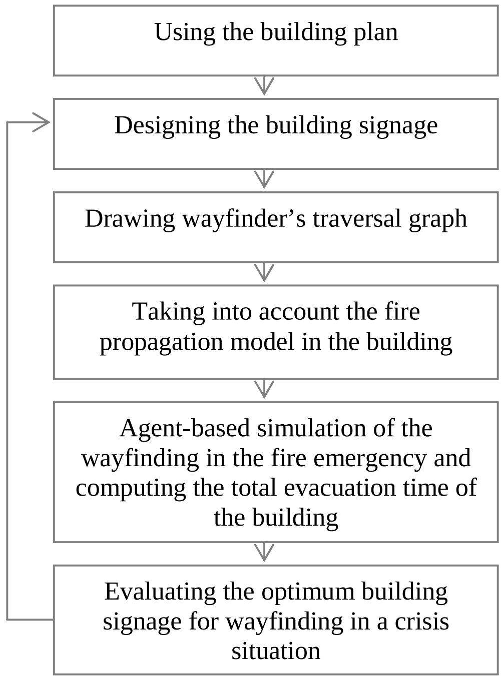

Fig. 3. The agent-based simulation of the wayfinding task

To represent and simulate knowledge and action in such a wayfinding situation, we design the building signage and a wayfinding traversal graph in the building plan. We begin the cognitive wayfinding task from a point which is a door of a section to the first decision point that is point 2 as shown in Figure 4. Then the possible ways to take are 2.1 and 2.2. One of the dashed edges is obstructed because of fire, smoke or design of the building and the other is going to the elevator which can not be used in fire emergencies.

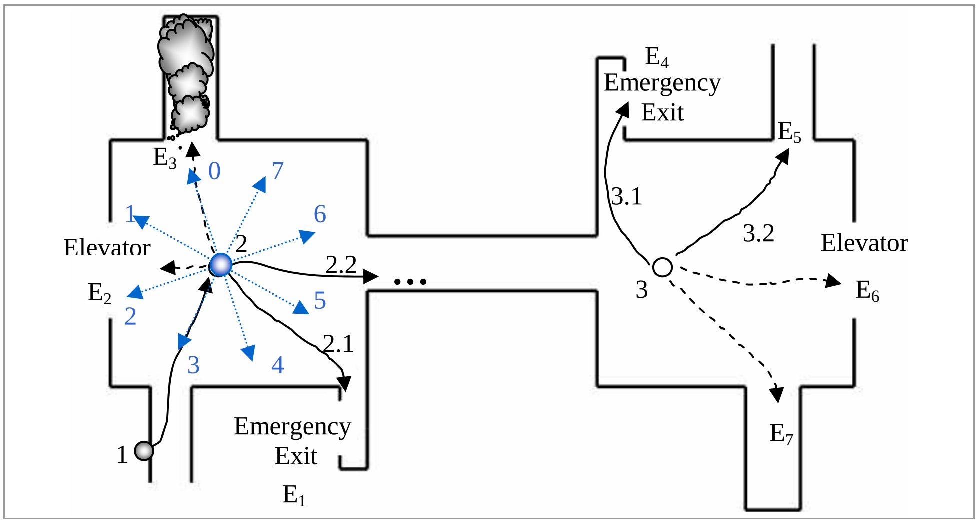

Fig. 4. The wayfinding plan

When people are either familiar with the environment or have access to a map of the environment, the process of decision-making would be easier. This is not the case when finding one's way in an unfamiliar building; therefore, we propose to model the preference as preferred directions within the agent's egocentric reference frame[16]. This reference frame is represented through eight directions; front, back, left, right, and the four directions in between [16].

A wayfinding strategy using preferred directions serves as the utility function, allowing the cognizing agent to make a rational decision when more than one path leads from a decision point to the goal. The utility function in the agent's model takes preferred directions of the agent into account and thus allows for ordering multiple solutions to the continuation of the wayfinding process at a decision point according to associated degrees of utility.

We assume that people prefer to continue along a path in directions in front of them instead of turning around and going side or backwards. Figure 5 shows the directions with their corresponding preference values, 1 being the highest value. This wayfinding strategy is an assumption and needs to be confirmed by empirical human subjects testing. In the case of a falsification of our hypothesis, the preference values can be easily changed without influencing the other components of the agent [16].

Table 1 shows the positions of the cognizing agent and its next situations in the wayfinding task. Because of the stressful situation of fire emergency, the cognizing agent would decide the 2.2 path which has a longer distance to the exit ways. This path reaches the decision point 3 that goes to the exit ways through 3.1 and 3.2 edges. Again, the edge

3.1 would reach the destination at a shorter time. This simulation continues until the wayfinding agent exits from the fired building.

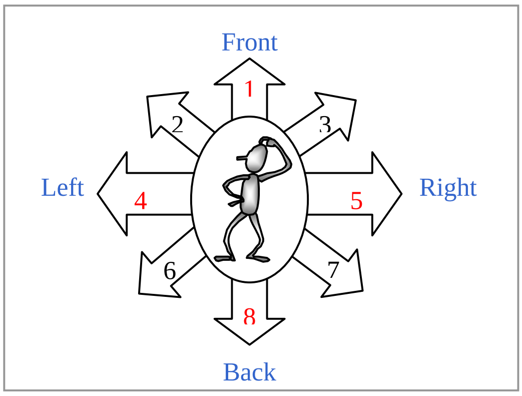

Fig. 5. Directions within the agent's egocentric reference frame and their corresponding preference values

Table 1. The wayfinding environment situation

Position	Go-to	Situation
1	2	First Decision Point
	E_1	Emergency Exit
2	3	Next Decision Point
	E_2	Elevator
	E_3	Smoke
	E_4	Emergency Exit
3	E_5	Go To Another Decision Point
	E_6	Elevator
	E_7	Obstructed Way

Because of the dynamic nature of fire, the propagation rule of the fire and smoke, that has a great effect on the occupants in their wayfinding abilities, would also be considered in order to model the agent's escaping from the burning building. This dynamic process is also simulated with the consideration of used materials in the building structure and time period with the help of some existing propagation models [13]. The stressful situation in a fire emergency also affects human behaviors in the wayfinding task [9]. For example, they may randomly select the longer or obstructed way (dashed edges in Figure 4).

The agent follows the information cues, makes decisions and moves in the virtual environment in order to reach the exit ways of the building. Neither the ability to learn nor a lasting cognitive-map-like representation of the environment is involved in deciding upon and taking an action. The cognizing agent's decisions and actions are based on wayfinding strategies and common sense reasoning. Based on the knowledge in the world, the wayfinder takes a sequence of actions until the wayfinding task is completed. Starting with imperfect observations of the space, the wayfinder derives incomplete and imprecise knowledge and based on such knowledge takes an action. Actions lead to further observations and knowledge, recursively to further actions until the goal, that is fire building evacuation, is reached [8]. In this paper the total time consumed to escape from the building is computed in order to evaluate the signage planning and achieve the optimum evacuation time.

4 Simulation

In order to clarify the concepts and methods used, we describe a case study that illustrates the situation in which our approach applies. It concerns the problem of wayfinding in a hospital in a crisis situation, specifically a fire emergency [7]. In this simulation the environment is a complex multi-floor hospital with various exit ways such as emergency stairs and elevators. The hypothesis of the simulation is that we have considered every person an average one who is young, not sick or injured and would sense the environment well. The intuition is that the nodes of the graph represent states of knowledge and current location in the wayfinding process, while the edges represent transitions either between views or between states of knowledge (Figure 6).

In a multi-floor building, the exit emergency stairs connect the floor plans which are one of the agent's exit ways of the building. If all of the people in the building were moving to the exit, then there would be a crowd and the agent would encounter difficulties in moving and this would affect the timing as well. Therefore, windows of the first floor would also be possible and sometimes safer exit ways in a fire emergency, especially if the exit ways are too crowded to be able to evacuate through in a short time, one would rather exit from the nearest windows. The wayfinding environment is simulated with due attention to the dynamic nature of fire and the agent's process of wayfinding in such a stressful case (Figure 7). Applying the same wayfinding agent in some other complex buildings and comparing the evacuation time from them, would determine the most efficient building design from the wayfinding point of view to facilitate crisis management in fire building emergencies [7].

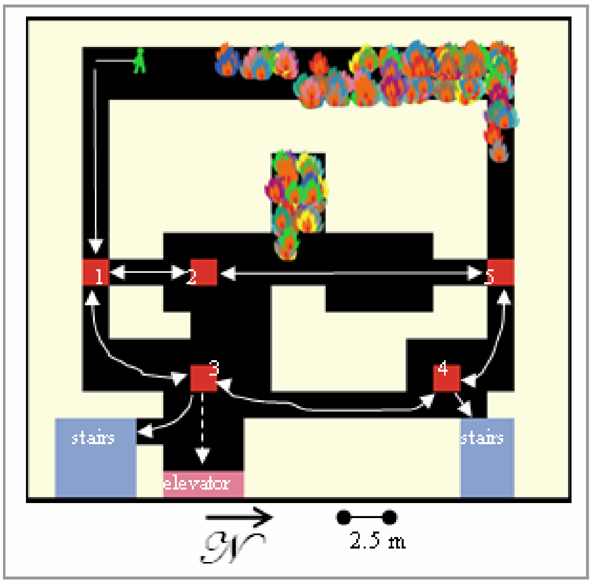

Fig. 6. The wayfinding graph in the hospital plan [7]

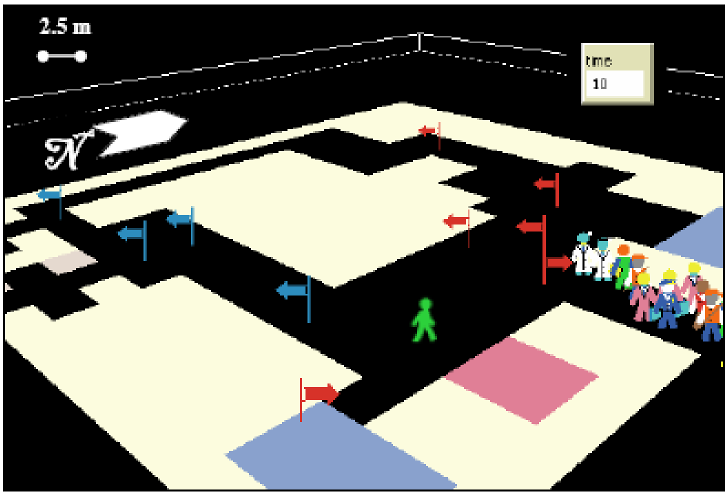

Fig. 7. The wayfinding plan [7]

In order to simulate the wayfinding process and dynamic propagation of fire in the hospital building, we have programmed the task in a simulation environment ,NetLogo, and computed the different evacuation times and found the best placement and design of the cues and landmarks in the hospital. Wayfinding through the optimum building signage would take the shortest evacuation time in a crisis situation. The simulation results have been compared in different designing situations (Table 2).

Table 2. Comparing Total Evacuation Time due to Signage Design

Different designing situations in the hospital	Total Evacuation Time of the Building (s)	Total Evacuation Time of the Building due to Optimum Signage Design (s)
A	83	31
B	52	17
C	53	11

In the above table, A is the case with the worst signage design but we have applied the quantity and placement modifications on it, so the total evacuation time has been reduced. B is the situation with a sufficient quantity of signage in which the placement of signage has been improved and C is the case with the optimum placement of the signage. It can be observed from the results that in all of the signage design situations, the total evacuation time have been reduced due to better placement of the cues and optimum determination of the quality and quantity of the signage [7].

5 Conclusion and Future Directions

A number of methodologies have been discussed for determining optimal and robust tactical and operational agent-based strategies for rapidly evacuating a large burning building. These procedures explicitly consider the inherent dynamic and uncertain nature of circumstances requiring evacuation. Therefore, they give rise to robust agent-based evacuation plans with lower probability of failure than paths determined otherwise, enabling faster and more efficient evacuation of a building in the event of fire, or other circumstances warranting quick escape.

This paper takes the agent-based simulation and determines an optimal plan to evacuate the building in the shortest time possible. Agent simulation for crisis management improves upon other simulation models that are concerned with numerical analyses of inputs or amounts of people and structures. This feature serves as an improvement to programs that only allow the agent to specify the occupants to follow the available paths considering the location of the fire or threat. The agent-based system for crisis management is grounded on empirical data taken from real-world experiments. If the agent sees an exit, it will proceed towards it and if it receives any types of direction to leave, that will be carried out without failure. The results show that the better placement of the cues and optimum planning of the quality and quantity of the signage lead to shorter evacuation time from the building.

We proposed in this paper formalized strategies which describe how spatial cognizing agent can find the exit ways in a building fire emergency by the use of the building signage in such a crisis situation. The novel approach is to describe how agents would cognize the environment's landmarks during the fire building evacuation process. Of particular importance is the ability of the agent to adapt his mental representation of the environment through perception of information from the real world. If we are interested in the state of knowledge of a person at different stages in the wayfinding process, then this may also be derived from the wayfinding graph. However, care is required here, as knowledge is not just dependent upon the viewpoint. It might be the case, for example, that the person returns to a point previously visited, in this case, it is likely that the point will be revisited with increased knowledge. This might happen because of the stressful fire situation that leads to such mistakes by the escaping person.

In all of the signage design situations, the total evacuation time have been reduced due to better placement of the cues and optimum determining of the quality and quantity of the signage.

This research integrated elements of people's perception and cognition, therefore, focusing on how people make sense of their wayfinding environment. Our work showed that it is possible to provide a formal framework of the process of wayfinding that integrates parts of people's perception and cognition with information and possibilities for action afforded by the wayfinding environment such as a fire emergency. The wayfinding graph provides a discrete, dynamic model of knowledge and action as the wayfinding process progresses. Such a model, based on transitions within a finite graph, is computationally tractable and allows computer simulations of wayfinding that take into account knowledge in the world and knowledge in the head. The model is of course only an approximation to the real process of human wayfinding and further work is required to determine how closely it approximates to wayfinding in the real world. For example, color of signage and individual wayfinding criteria such as minimizing travel time or stress might be additional factors that need to be built into the model. Evaluations of the performance of the model also have been done in this research.

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