Modeling and Simulation of the Evacuation Plan for Hancock Stadium

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Abstract

The goal of this study is to use modeling and simulation of evacuation plan (MSEP) to support management to execute proper evacuation plan in case of emergency at Hancock Stadium in Illinois State University. The analyses of research literature and evacuation scenarios are used to build a simulation system that will connect a description of emergency and evacuation situation with its context. It shows how an evacuation plan actually functions. The results of the study will help safety managers to understand the current situations of evacuation according to the specific simulation scenarios. The evacuation simulation is categorized according to the types of emergent situations and the number of evacuees. Each simulation is validated according to the real time data collected through observations and the published literatures. The practical implications of the research include the developed system to be used in case of emergencies and the experience gained will help future design of large-scale venues and facilities. This research innovatively used Building Information Modeling (BIM) technology, Dijkstra and Open Cleared Path algorithms, and Pedestrian Dynamics® simulation system for an open-space, steel structure in evacuation routes.

INTRODUCTION

Safety Issues in Large Crowded Areas

Handling a large number of crowds in a limited area is critical and essential for the safety of people. Especially in those places, such as stadiums and arenas, where a large number of crowds get together, proper plans should be provided to avoid the catastrophic incidents in case of emergencies. The plans should focus on the evacuation of everyone within safe time-fames and with minimum-possible damages. For example, the evacuation scenarios should be defined and implemented. The scenarios for fire and for tornado are different and their variables vary as well. In addition, many issues have been found in emergency evacuations where a large number of crowds get together with limited access routes and exit doors (Baker, 1991; Pan, et al., 2007)).

Even though safety management is essential for buildings, the lack of the development of evacuation technology still exists (Basha & Rus, 2007; Wolshon, et al., 2005). One reason of the lack of studies is the difficulty to define the variables and evacuation situations. Defining the variables is extremely critical (Lindell & Prater, 2007). High uncertainty of the variables is the hurdle in the path of searching for the best evacuation plan in case of emergency. Emergency situations happen randomly. Currently, to design and arrange the response to the unforeseeable emergency situations, researchers use proper algorithms to generate productive evacuation plans for possible evacuation scenarios (Lu, et al., 2005).

Parametric Modeling of Stadiums

Variables in simulations have certain similarities with parameters in the models or projects of Building Information Modeling (BIM). Variables are used to describe the evacuation situations. Comparably, parameters in BIM models are used to describe objects' behaviors, restriction, constraints, and parametric rules. Particularly, parametric models of buildings and facilities can be used together with evacuation software to improve the numerical simulation of evacuation plans, which increase the power, accuracy, and ease of the evacuation processes in planning and designing of large crowd-gathering places (Fu & Wilmot, 2006; Rüppel & Schatz, 2011). Immediate results of the evacuation simulations become possible by using real-time systems. The results can be used to predict the best plan for an emergency situation with computed reliability. However, researchers and practitioners still have concerns with the reliability of the modeling and simulations because the calculations are performed in virtual conditions. Various unpredictable situations happen in the real world. Observations, studies, comparisons, and analyses must be conducted to calibrate the mathematical modeling and simulation results for emergency plans.

This paper highlights some of the issues by categorizing them to technical, sociological, physical, and resources aspects. Particularly, this paper presents an evacuation system using simulation models for the Hancock Stadium's emergency management. The main parameter of the research is the Total Evacuation Time (TET). The authors compare the results calculated by the proposed simulation model with a real situation of emergency evacuation. To perform the comparison, the authors compare average real evacuation time and average simulated evacuation time to verify whether the calculated data reflect a real evacuation. Statistical one tail T-test and Mann-Whitney U-Test are used to analyze the two means, which are real evacuation time (TET1) and simulated evacuation time (TET0) with 90% confidence level.

Null hypothesis H0: TET1 = TET0
Hypothesis H1: TET1 ≠ TET0

LITERATURE REVIEW

There are two types of techniques for the agent-based models: time-sliced and event oriented models. They are used to schedule the functions based on the time or corresponding queue of instructions. The microscopic and macroscopic techniques used in the models build the simulations based on the levels of details needed. Macroscopic technique uses group-level mathematical models to simulate the continue simulations. Microscopic technique uses the details of individual agents with more functions. Therefore, the agent-based methods offer attractive benefits, i.e. producing realistic and detailed simulations. In this case, agent-based methods are implemented for modeling the large-scale evacuation. Xie and Li (2014) argued that an evacuation model should focus on 3 major tasks, which are (1) move to the nearest exit, (2) try to move to the area with low crowd density, and (3) try to avoid obstacles on evacuation route. These 3 tasks become complex with the increase of the size, capacity, and design of a floor plan of a stadium. The speed of an individual and the direction of the movement are used as the parameters of the simulation of an evacuation process. The major tasks described by Xie and Li (2014) were also used in this research as part of the agent norm when the authors simulated the evacuation scenarios in the selected environment. The walking speed of a pedestrian is determined solely by the density of the surrounding pedestrians according to their moving speed, and the behavioral characteristics of the pedestrians (Wang, et al., 2013). Evacuation processes may differ due to the causes of evacuations, such as fire, lightning strike, and man-made incidents. Researchers argued that the multi-model and multi-agent system could generate an evacuation simulation close to real evacuation process. It's necessary to have a smooth connection between models and evacuation strategies to make an evacuation process productive and efficient. Various kinds of models and tools are built for evacuation simulations. For example, using CD++ toolkit; the Cell-DEVS (Discrete-event systems Specifications) modeling environment can be implemented to run the evacuation simulations remotely (Wang, et al., 2013). It can load IFC files through the BimServer.org. Figure 1 describes the how BIM framework works for simulation uses.

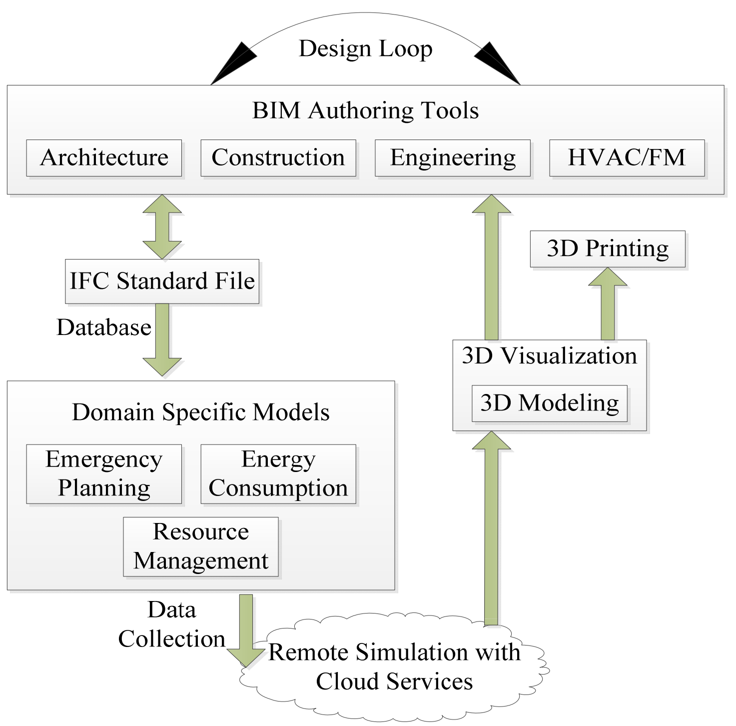


Figure 1. BIM Framework

The approach described in Figure 1 aimed at the real-time crowd behavior at a facility. The feature of the evacuation software included collision-avoiding and crowd behavior functions. Cell-DEVS model was an indoor navigation system. It was similar to GPS, but with more accurate details of the positions of the agents, which are virtual representations of audience. In the situation when everyone uses a smart phone or a smart device, this technology can broadcast evacuation routes to every device. Evacuation management projects need to connect well between the layers of hardware, communications, and applications. Evacuation simulations can be built with, not only to display the crowd behavior, but also to simulate the operations of alarm systems, dynamic signage, and other operations (Chiu, et al., 2007). These simulations are based on various methods such as discrete method, agent based, Cellular Automata, particle dynamic, and continuous method. One of the most widely used methods is agent-based simulation method. Its techniques include collision avoidance and behaviors modeling. The agent-based system combined with Local-Versus-Global technique can produce an indoor and outdoor navigation for agents.

Simulation software can generate detour routes, but the routes are limited during an evacuation simulation. The field of evacuation studies is attracting more scholars' attentions due to the high needs for the public safety. Therefore there is a high demand for this type of software applications. Most of the simulation software applications are expensive in the market. The cost is a major limitation of the software product. Pedestrian Dynamics (PD) simulations can imitate specific evacuation scenarios. However the simulation does not exhibit human behaviors and their associated risks in real emergency evacuation. One major limitation is that there is no proper way to profile an agent with social and psychological intelligence or with assessment capabilities. The simulation software has some advanced features such as collision detection, collision avoiding, and intelligent movement dynamics.

SYSTEM DESIGN

The objectives of safety in a business include saving lives, reducing injuries, and protecting assets. It's a law to have evacuation plans and procedures according to OSHA (Occupational Safety and Health Administration) for public facilities (OSHA, 2015). Hancock Stadium already has an evacuation plan for emergency and regular conditions. But it has never been tested or used in a true emergency situation, because it's difficult to simulate a real emergency situation. This research on the Modeling and Simulation of Evacuation Plan (MSEP) establishes a comprehensive plan based on these simulations and helps to catch latent emergent situations.

The flow chart in Figure 2 shows the design of the simulation system. The first step of the design is to identify the number of occupants in the stadium. This paper focuses on the scenario of approximately 1,000 occupants in the building. The capacity of the stadium is 7,500. When the number of evacuees increases, it is riskier to form up certain hazardous conditions in the facility. The number selected provides a good understanding of the mass behaviors in a manageable evacuation process. The next step is to check whether the data is from a real-time observation or a simulation. The simulation results are automatically generated after the simulation is done, but the video files have to be analyzed manually. After that, the system receives the data when a random exit is blocked. The final part of the research is to obtain the data and generate reports.

Data Collection

The authors collected data through onsite surveys regarding how long it would take a regular person to leave from one random seat in Hancock Stadium in different conditions. Figure 3 shows the seating chart of Hancock Stadium. The numbers of 1 to 5 represent the 5 zones the authors observed from real situations. The zone with ID number of 1 was selected from the areas that are close to exits. Zone #2 is relative far from the exits. Zone #3 was picked from the areas that the audience needs to travel up the stairs and go against the direction of the major flow of withdraw. Zones 4 and 5 are even further away from the exits of the stadium. Because one focus of the research is the Total Evacuation Time (TET) when all the audiences leave the stadium, the measurements obtained from the observations on Zones 4 and 5 are critical to TET.

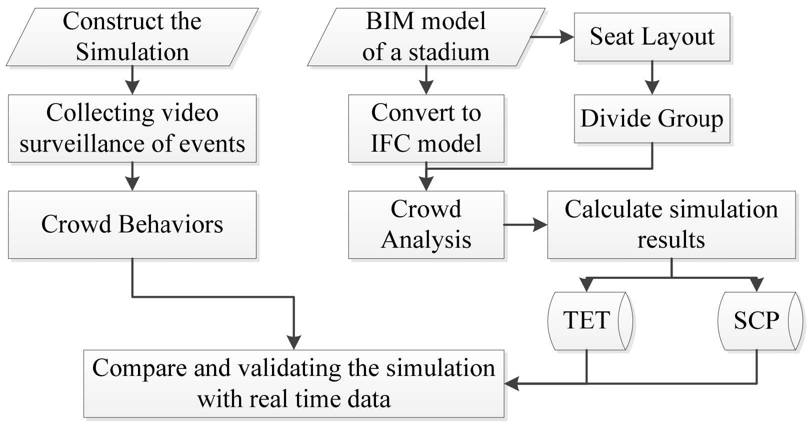


Figure 2. Design of the Simulation System

Figure 3: Seat Zones in the Stadium (Planning and Facilities Services, 2013)

In this research, an ideal condition meant that an individual was able to move freely without any crowd interactions. According to the collected data, the authors discovered that an individual could leave the stadium from a random seat in between 15 and 97 seconds with no crowd interaction. One group of scenarios discussed in this paper was close to this ideal situation. When the audience number in the stadium is around 1,000, which is much less than the overall capacity of 7,500 of the stadium, the audiences can leave the stadium without excessively impeding each other. In contrast to that situation, when the audience number in the stadium reaches approximately its maximum capacity, the crowd interactions or possible bottlenecks would happen frequently. Table 1 shows the sample data collected from surveys when the audiences in the stadium reached 7,500. In Table 1, the first column has the zone numbers marked in Figure 3. The second column includes the seat numbers (column/row). The next 3 columns in Table 1 show the data collected from 3 different scenarios. In all the 3 scenarios, the total audiences were around the full capacity of the stadium (7,500). Therefore, the audiences in the observed situations could not leave the stadium without considerably interaction. There is no major difference between the 3 scenarios. As the data in Table 1 show, it might take a person 1 hour 36 minutes to travel from a seat far from an exit to leave the building. The data in Table 1 were collected under non-emergent situations. The audiences were unaware of the observations. One limitation of the data in Table 1 is that the weather conditions were not considered. In the future, the influences of weather conditions might be included for further research.

Table 1. Observed Evacuation Time from Randomly Selected Seats

		Time To Nearest Exit		
Zone #	**Seat Number**	**Scenario 1**	**Scenario 2**	**Scenario 3**
1	5/22	00:13:86	00:14:66	00:15:80
2	56/8	00:36:98	00:34:00	00:36:44
3	23/5	00:56:32	00:58:20	00:57:90
4	39/9	01:06:65	01:04:12	01:06:12
5	5/11	01:36:60	01:37:91	01:36:45

The authors noticed that design components could be affected by the BIM model under different seat design and scenarios. For example, the shortest time happens to those people who stayed at the corner bottom rows of the bleachers. The people at the members' areas took longer time to evacuate in the ideal conditions. Some seats in the bleachers require the audiences to go up the stairs and against the major flow of the withdrawal to the exits. In addition, the authors also noticed that there was no designated route of evacuation for people with disabilities in the stadium. People with disabilities need to share the routes and exits with the crowds. In case of emergencies, it is highly possible to cause evacuation bottlenecks in the crowds.

Calculation Methods

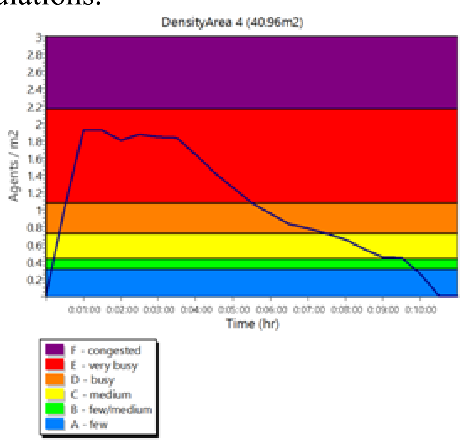
The simulations automatically indicated the TET at the end of each process. But the calculation on the TET based on the data collected through observations for the validation purposes was conducted manually. The crowd density was calculated for the crowd-handling purposes. The simulation automatically calculated the average time from every exit. The following process is an example of the manual calculation of a real situation from a survey.

Number of exits	= 5
Average travel time	= 25:46
Number of evacuees	= 1,000
Average number of evacuees in an exit	= 1,000 / 5 = 200
Density per second	= 200 / (25*60 + 46)
	= 0.1294 Persons/Second

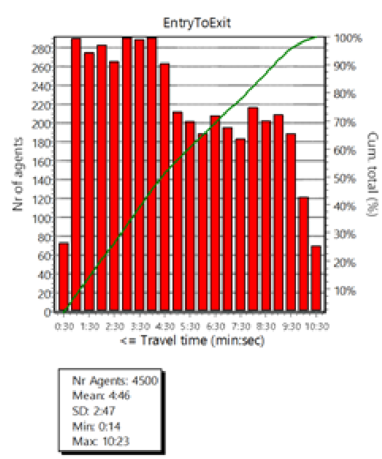
The maximum, minimum, and average distances were also calculated for the enhancement of the evacuation plan of Hancock Stadium. Calculations were done for both the evacuation simulations and observed data. If the evacuation has occurred due to an emergency, the response time was calculated for the analysis. The response time is the time taken for the first evacuee to reach an exit after the evacuation is triggered. When the response time decreases, the quality of the evacuation increases. Cx (Capacity of exits) was calculated manually, it was a fixed value. Vx (Volume of the crowd in an exit) was a dynamic value, which changed in every evacuation scenario. Pedestrian Dynamics calculated the Vx for every evacuation scenario. Some manual calculations were done for the validation of the parameters. Because of the random and dynamic behaviors of the crowd, it was a challenge to manually calculate the SCP (Shortest Cleared Path) for every timeframe.

Calibration

Figures 4(a) and 4(b) below are for the situation when there are approximately 4,500 agents generated to simulate the evacuation situations in the stadium. The number of 4,500 was carefully selected to calibrate the simulation system. The focus of this research was on the simulations and analyses of the evacuations of 1,000 audiences. Considering the overall capacity of the stadium of 7,500, the number of 4,500 is in the median number between. The calibrations help to train the simulation system and define the agent norm. The authors were particularly interested in the following characterization: (1) the agents in this multi-agent system have simultaneous moves; (2) the agents coordinate their actions, with adoption and adherence to the directions to the exits; (3) the agents are able to learn and evolve to reduce disagreements, which will promote the intelligible behaviors and reduce deadlocks. The interaction of agents was defined as an equilibrium. Every agent is in the interactions that have more than one equilibrium. This definition has particular significance for the research in the context of computational agents in the evacuation simulations.



(a)



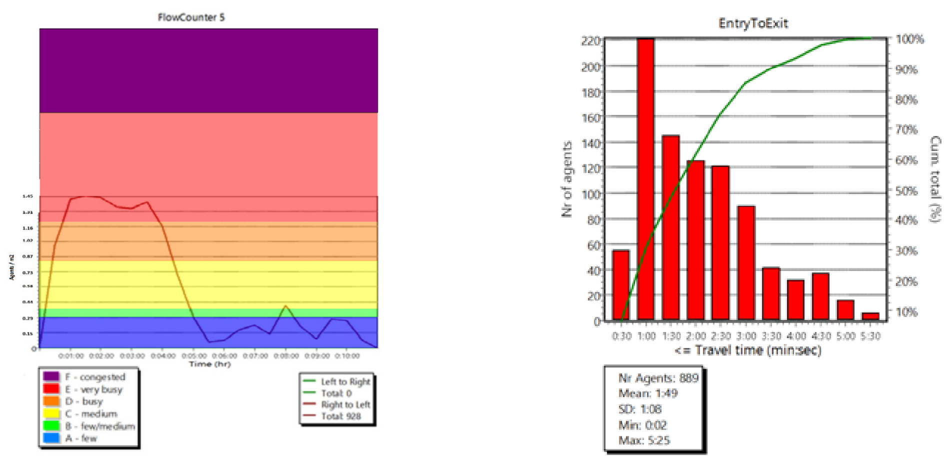
(b)

Figure 4. Calibration: Density of an Exit during an Evacuation and Evacuation Behaviors of Agents

As shown in Figure 4(a) and 4(b), the numbers of calibration plots were used to show the dynamics of the crowd behaviors in the stadium. In the research, the selection of the calibration plots was based on the following considerations: (1) It is important to find out the crowd density at a location during an evacuation. (2) The places near exits have higher density than any other places in the stadium. Therefore, the authors measured the crowd densities over time near the exit areas to analyze the risk factor of crowd bottleneck. Figure 4(a) shows a calibration plot of how many agents per one square meter over time near a specified exit area. The calibration plots in Figure 4(b) show the evacuation behaviors of agents during evacuations over time. It also generates the maximum and minimum time taken for an agent to evacuate from the facility. The important statistical data such as the standard deviation (SD) and the mean are also displayed in the plot.

Results Analysis

After the calibration process, the simulation system was used to collect data and analyze the situations when there were around 1,000 audiences in the stadium. The authors used the floor counter to understand the crowd behavior dynamics at different places in the facility, such as stairs, corridors, and exits. The plot in Figure 5(a) shows the numbers of the agents moving across a specific place over time. The data in the graph show how the crowd density changes over time and location. The graph also indicates the directions of the flow. For example, the number of people who move across the line to one direction and the number of people who move across the line to the opposite direction. Since this is an evacuation process, it is important to know whether the crowd moves to the same direction and the direction to go out of the facility. Figure 5(b) shows the crowd behaviors when moving toward the direction of exits during evacuation.



(a) (b)

Figure 5. Evacuation Behavior in 1000EVAC

Figure 5(a) shows that for more than 60% of the time, the stadium floor was in the crowd conditions of either few, few/medium, medium, or mild busy situation. For the comparison between Figures 4(a) and 5(a), there were less amount of time and agents in very busy condition in Figure 5(a). In addition, Figure 5(a) shows that after the first 5 minutes, the stadium floor would have most of the areas in few or few/medium conditions of the crowd. Figure 4(a), instead, shows that the reduction of the crowd intensity was relatively gradual. It took the crowd more than 9 minutes to reach to the few or few/medium conditions. The comparisons between 4(b) and 5(b) also support the same inspections.

The Hancock stadium evacuation simulations have generated numeric important results for researchers to analyze and enhance the safety of the facility. Results indicate that the TET varies from 4:45 minutes to 20:20 minutes based on number of evacuees. As Figure 5(b) shows for a scenario of around 1,000 audiences, the total evacuation time varies in between 4:45 and 5:25 minutes. The average response time is 15 seconds. The mean is 1:49 minutes. According to the data, a person could evacuate the facility within 15 seconds if the occupant is near the bottom rows of the bleachers. People from the members' area could take more time to evacuate because of the seat layout and the design of the stadium.

The authors also performed the analysis of the crowd flow in an emergency scenario with a random blocked exit. In this scenario, a random exit door is blocked but with the same number of evacuees. The TET of the scenarios of 1000EVAC in an emergency with a random blocked exit is 5:25 minutes. When the east corner exit is blocked, it takes 40 seconds more to evacuate the entire crowd. In these scenarios the density of exits is increased during the first 1:00 to 2:30 minutes of the evacuation process. During these periods the average density of an exit is 2.2 persons per square meter, which creates congested condition.

DISCUSSION

Further results showed the significant change of evacuation durations when the number of crowds gets increased. The risk of crowd bottleneck is high in an event such as homecoming, when all the seats are taken by the audience in the stadium. According to the conversations with the safety management officials of Hancock Stadium of ISU and the observations of the author, the access routes and exits of the stadium had enough space to evacuate crowds from the building. However, some places such as the access stairs to the bleachers tended to be easily blocked during a full-scale evacuation.

Another finding from the data analysis showed that the simulation results reflected the real evacuations in Hancock Stadium to a limited extent. With the definitions of null hypothesis and an alternative hypothesis stated at the Introduction section of this paper, the authors accepted the alternative hypothesis and rejected the null hypothesis, because the simulation results did not confirm with the real evacuations. The reason for the difference is that the virtual agents in simulations are not programmed with enough capabilities to reflect the moving dynamics, but the TET of the simulation results is generally longer than the observed data. The simulation system is relative conservative in the estimation of total evacuation time. The simulation results identify potential problems and provide suggestions to the safety management plan.

CONCLUSION

In order to evaluate and improve the evacuation plans of stadiums, this paper proposed the evacuation simulations to predict the crowd behaviors for crowd evacuation scenarios based on Pedestrian Dynamics multi-agent software solution. The simulation model reflected the characteristics, laws, regulations, and standards of crowd evacuation. This simulation model was capable of dynamically changing to the local conditions. This model generated valuable statistical graphs of crowd dynamics. It gathered the data such as crowd bottleneck areas, the density of the crowd, and the average speed of the crowd. The content of the paper provides the scientific and ethical analysis of crowd evacuations in stadiums.

Acknowledgments: The authors would like to thank the Facility Management group and the safety management officials of Illinois State University for providing the documents and data to support the research.

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