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Modeling and Simulation of Evacuation Plan for Hancock Stadium

Nirmal Neranjan Weerasekara
Illinois State University, nnweera@ilstu.edu

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MODELING AND SIMULATION OF THE EVACUATION PLAN FOR HANCOCK STADIUM

Nirmal N. Weerasekara

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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. Analyses of the 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.

MODELING AND SIMULATION OF THE EVACUATION PLAN FOR HANCOCK STADIUM

NIRMAL N. WEERASEKARA

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Fulfillment of the Requirements
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MODELING AND SIMULATION OF THE EVACUATION PLAN FOR HANCOCK STADIUM

NIRMAL N. WEERASEKARA

COMMITTEE MEMBERS:

Haiyan Xie, Chair

Klaus Schmidt

Anu Gokhale

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N. N. W.

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CHAPTER I

INTRODUCTION

Background of the Research

Sport stadiums provide iconic locations for sporting, entertaining, performance, exhibition, and other social or cultural events, which attract people from all around. Some people may travel hundreds of miles to watch an important event, such as a football championship game. But there is a public safety issue with all sport stadiums. Stadiums create an enormous space to hold a large crowd. There are potential risks of mass distraction conditions. In stadiums, large groups of people gather together in a limited space for extended periods of time. Under the circumstances of natural disasters or anthropogenic (human-made) hazards, such as fire or structural collapse, the crowd inside a stadium needs to be evacuated. Stadium facility management needs to have a valid and qualitative evacuation plan to evacuate the crowd safely and effectively. Historically, people had to manage both natural and man-made emergencies to ensure the protection of lives and properties. In order to avoid the losses caused by the disasters or hazards, governments and private agencies have been spending their time and money to develop specific safety evacuation plans for individual facilities to ensure the safety of people and/or important goods. With the emerging of visual simulations and 3D modeling techniques, researchers can now use modeling and simulation tools to gain increased understanding of a crowd's social-psychological behaviors.

Particularly, parametric models of buildings and facilities can be used together with evacuation software, to improve the numerical simulation of evacuation plans. Those new technologies increase the power, accuracy, and ease of the evacuation processes in planning and designing of large crowd-gathering places. Immediate results of the evacuation simulations are becoming possible by using real-time systems. The results can be used to predict the best plan for an emergency situation with computed reliability. But researchers and practitioners are still concerned with the reliability of the modeling and simulations because the calculations are performed in virtual conditions. Because of the various situations in the real world, observations, studies, comparisons, and analyses must be conducted to calibrate the mathematical modeling and simulation results for emergency plans.

Many organizations have emergency plans or guidelines. According to the Campus Safety and Security statement of Illinois State University (Illinois State University, 2014), the university "is committed to providing a secure and welcoming campus environment for students, faculty, staff and visitors" (Illinois State University, 2014). The evacuation-route planning is the major and critical objective of the evacuation plan of the Hancock Stadium on ISU campus. The stadium is capable of facilitating almost 10,000 audiences. It might become a high risk of hazardous condition when the large number of crowds suddenly moving out of the facility. In order to build a well-organized evacuation plan, efficient methods are needed to identify the exit routes and schedules.

Purpose of the Thesis and Research Question

The purpose of this research is to provide mathematical calculations to analyze the evacuations methods. Using evacuation simulation models lead to the optimization of possible evacuation routes in the stadium. The evacuation models are built according to some advanced algorithms and including the parameters of crowd-moving characteristics. Identifying the evacuation parameters is critical to any evacuation plan. The objectives of this research include the following (1) study the parameters of evacuation plan by using Hancock Stadium of ISU: (2) use Building Information Modeling (BIM) technology and Pedestrian Dynamics® software to design and implement a simulation system for the improvement of evacuation plans; (3) provide optimized egress-route suggestions in real time.

The research question in this study is: “Do the results calculated by the proposed simulation model reflect the real situations in Hancock Stadium?” Particularly, the author used Tekla® as the BIM tool to provide highly detailed, 3-dimensional parametric structure models of the facility. The Tekla® model can be combined with the basic evacuation algorithms, such as the Dijkstra’s algorithm, open shortest path algorithm, and open-cleared-path algorithm, to build the simulation models. In this research, the algorithm included two major parameters, which were Shortest Cleared Route (SCR) and Total Evacuation Time (TET). The research results showed the optimization of the escape routes based on SCR and the shortest time from the location of each individual in the audience. The author also considered the horizontal and vertical travels of the evacuation, which could provide more advanced and effective exit routes. The final product of the Modeling and Simulation of Evacuation Plan (MSEP) for the Hancock

Stadium would improve the emergency management process for disaster preparedness and response.

Significance of the Study

Since disasters are unpredictable, it is an impossibility to simulate an evacuation in case of a real emergency. In this research, the author studied the evacuation simulations for the Hancock Stadium at Illinois State University to remedy the lack of information and reduce the uncertain variables, when building a simulation model. In this study, expert knowledge and experiences are reviewed to create evacuation simulations. The study has high significance to both the design and the implementation of an evacuation system for large gathering spaces. Safety is always the first priority in a public event such as a football game. The Hancock Stadium should have a high-quality evacuation plan to avoid hazardous situations or to minimize potential damage.

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 research findings also suggest that people should pay more attention to the handicapped areas in the stadium. In the future, people can add to this research with the variables to reflect human behaviors, such as the behavior affected by alcohol and a potential state of panic when an emergency occurs.

Assumptions

The assumptions made in the study are listed below:

1. All the exit routes are clear.

   This assumption is made to ensure that the evacuation routes are ready-to-use in the process of evacuation according to the simulation.

2. The crowd is aware of exit doors and evacuation procedures.

   This assumption is to avoid the unexpected crowd bottleneck in exit routes.

3. Emergency power supply is ready or in use.

   This assumption is made to ensure the visibility of the exit routes to avoid crowd panic. The assumption assures clear views in case of emergency.

Hypothesis

The main purpose of this thesis is to suggest an evacuation system using simulation models for the Hancock Stadium's emergency management. The main research question is based on the Total Evacuation Time (TET). The author will compare the results calculated by the proposed simulation model with a real situation of emergency evacuation. To perform the comparison, average real evacuation time and average simulated evacuation time will be compared to verify whether the calculated data reflect a real evacuation. Statistical one tail T- test and Mann-Whitney U-Test be used to analyze the two means, which are real evacuation time (TET_1) and simulated evacuation time (TET_0) with 90% confidence level.

H_0: $TET_1 = TET_0$
H1: $TET_1 \neq TET_0$

Definitions of Terms

H_0- Null hypothesis

H_1-Hypothesis

D_x- Distance to a nearest exit from and each individual location

T_x- Time taken to reach to an exit

C_x-Capacity of exits

V_x Volume of the crowd in an exit

SCP- Shortest Cleared Path

TET- Total Evacuation Time

Limitations

The following items are the limitations of the research:

1. There was no real field data to verify the simulation results of Hancock Stadium.

At the time of this research, there had not been any serious emergent evacuation in the history of Hancock Stadium at ISU. According to an interview with the stadium's safety officers, Dan Hite and Eric Hodges (M.A., CEM), on April 3rd 2015, there were no surveillance cameras installed in the facility. It was an obstacle of the research because the author was unable to analyze any video data recorded at the stadium for validating the evacuation simulation scenarios.

2. Expensive software.

Pedestrian Dynamics Studio software is industrial level software for simulations. It is expensive for the student users. The price of the annual subscriptions is $9,950.00.

3. Data might be skewed. The site data are measured from young adults. But general audience includes people of all ages.

4. The simulation did not consider power-outage situation.

Delimitations

The following items are the delimitations of the research:

1. The author used literature, data from other stadiums, and field tests.
2. The author used the trial version of the software.
3. The author added adjustment factors to the field data.
4. The simulation had both a power system and an emergency-backup system.

Summary

The purpose of this thesis is to study evacuation scenarios for Hancock Stadium using models and simulations. The main goal is to implement BIM-based simulations to enhance the evacuation plan of the stadium. The simulation is compared with real-time evacuation behaviors to ensure the accuracy and the validity of the parameters. The simulation and the model are built with assumptions based on unavoidable limitations. The evacuation model can assist safety authorities to compute the shortest path from different locations of the stadium with minimum bottleneck. It also calculates the shortest evacuation time. The study on the evacuation plans of buildings and structures provides safety and protection to the players and the audiences.

CHAPTER II

LITERATURE REVIEW

Public Safety and Simulation

Public safety is becoming one of the critical factors in every business. The field is getting more complex and expanding everyday due to the rapid development of the human activities. Scientists get more interested on the evacuation research. It becomes a necessary service in every facility because even buildings are identical; they have unique structural designs and geographical differences. Therefore evacuation plans vary from one building to another. An architect needs to understand the evacuation plan when he or she is planning the building design. The essentiality of an evacuation plan is to vacate a crowd safely as soon as possible. If a facility doesn't have a proper evacuation plan, a tragedy may happen with the losses of lives and property damages. The purposes of an evacuation plan are the safety of evacuees and properties. History provided best examples of the essentiality of a proper evacuation plan. For example, 21 persons died in a nightclub incident in Chicago, IL in 2003 (CNN, 2005). There were 602 people died in a fire Iroquois Theater in Chicago, IL in 1903 (EASTLAND MEMORIAL SOCIETY, 2007). In the 2001 stampede in the Kinshasa Soccer Stadium, 120 people died because of police tear gas fire to control the trouble crowd in the stadium (NYDailyNews, 2015). Disasters could occur in any facility with a poorly designed evacuation plan.

Sport games attract the people from everywhere in the world and its getting more professional and interesting over the time. Sport games bring the unity and connection between nations globally. On the other hand, because of the huge sizes of audiences in sport games, people in the sport facilities could be the potential terrorist targets. The terrorist attack in Boston Marathon on April 15, 2013 (Massachusetts Medical Society, 2015), is an example that the terrorists wanted to get public attention by targeting on sport events. Three people were killed and 264 were injured from two improvised explosive devices (IEDs) in the 2013 Boston Marathon. It was the first incident to cause live lost and massive injuries in the history of the United States. Natural incident and man-made hazardous emergencies could also occur, which cause the potential life-threatening incidents to both sport teams and audiences. Sport stadium provides enough space to gather a large number of people for a limited times, hence the risk of mass destruction is high. That is the reason why a sport stadium should have proper safety and evacuation plans. The proper evacuation plans should be deployed to evacuate the teams and the audiences in a stadium without provoking damages to the properties and human beings. A stadium usually provides the following functions: (1) seating space for audiences; (2) space for teams in a game; (3) lighting, audio, video, and security devices; (4) space and functions for public media; (5) food service; (6) restrooms; (7) lockers; (8) entrance and exit control; etc. The multiple functions of a stadium makes the inside design of it complex and confusing to ordinary people. When evacuating a large number of crowds in case of emergency, it is very easy for people to get lost and panic if effectual and efficient evacuations plan is not deployed. Among the large-size facilities, sport stadiums are much different from other ones because their interior designs need to provide enough slopes for the audiences to watch the game fields. The steps and slopes in the stadiums could cause more hazardous than other facilities. When an incident occurs, the whole crowd in a stadium can catch the sight of the incident or disturbance. They all could be panic at the same time. Without any indication, the directions to leave the spot are not clear to the audience because of the interior design of the facility. That is the reason why a stadium should have a valid evacuation plan to avoid causalities and property damages (Graham & Johns, 2012). For incident prevention and avoidance purposes, governments also established the corresponding safety measurements and guidelines for crowd control at stadiums (Department of Homeland Security , 2008). The uncoordinated motion of the crowd may lead to jamming, pushing, crushing and trampling. In any of these circumstances, an individual's control over his or her own movement becomes impossible (Wang, Lo, Wang, Sun, & Mu1, 2013). Shock waves may propagate through the crowd mass and cause uncontrollable surges (Wong, Lo, Wang, Sum, & Mu, 2013). Hazardous incident could be generated during an unregulated evacuation process. Crowd density plays a critical role in the evacuation process. Relationships between the evacuation time, the nearest path, and the crowd density are the keys to build a proper evacuation plan. The speed of moving crowd should be regulated during evacuation because one of reason for the crowd bottleneck is the unregulated speed. Exits have limited spaces. Hence the crowd should move at certain speed. Sometimes evacuation path can be intentionally made a little longer to minimize the crowd bottleneck in a stadium in order to control crowd density.

Computerized evacuation-simulations have been identified as integrated solution for evacuation plans. They are created based on the recommended requirements by the authorities, such as FIFA (Fédération Internationale de Football Association), UEFA (Union of European Football Associations), and the government safety-enforcement officers. Software applications of simulations are capable of generating realistic crowd movements with 3D visualization. They provide the detailed output results based on industrial standards of drawings and models. Simulation software, which is specially designed for stadiums and arenas, can provide insight into visitor flows and possible bottlenecks in the modeled situation (INCONTROL, 2015).

Related Studies and Researches Simulation of Crowd Behavior

Evacuation simulations are built for each individual facility. Different evacuation models are based on various design strategies or data types. For example, Geographical Information System (GIS), Agent, Cellular Automata Model and BIM, are used to assist simulations. Various approaches are proposed for modeling movement and simulating multiple human beings (Manmarus & Zarboutis, 2007). In addition, researchers are studying the simulations of virtual or constructive agents. Virtual agents mean that real people operate simulated systems. Constructive simulations mean that simulated agents operating simulated systems. Agent-based methods can generate fast simulations using simple local rules that can create visually plausible flocking behavior (Manmarus & Zarboutis, 2007). Agent based models provides significant advantages for crowd simulations. The agent-based models are flexible and save time and cost. An agent-based system also provides a natural description of a crowd simulation. It can capture emergent phenomena, which means that the interaction between two or multiple agents can be identified. 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 recommended for modeling the large-scale evacuation. Basically an evacuation model focuses 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 (Xie & Li, 2014). The 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 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 (Wong, Lo, Wang, Sum, & Mu, 2013). The major objective of the evacuation simulation in this research is to identify a model, which has the least time taken during an evacuation process. One problem of the studies on evacuation simulation is to identify the smoothest evacuation route and simulate the evacuation situations on real-time. The evacuation process may differ due to the cause of an evacuation, 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 modeling and tools are built for evacuation simulations. For example, using CD ++ took kit; the Cell-DEVS modeling environment can be implemented to run the evacuation simulations remotely (Wang, Gabriel, Goldstein, & Khan, 2013). It can load IFC files through the BimServer.org. Figure 1 describes the how BIM framework works.

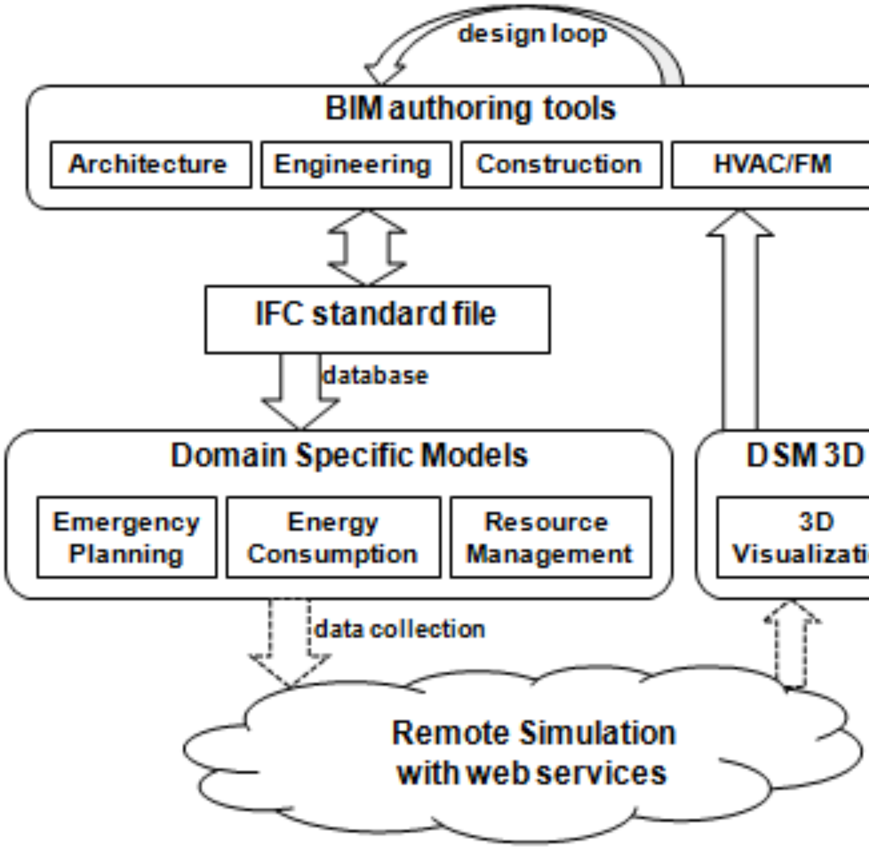


Figure 1: BIM Framework

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 such as 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.

Cellular Automata model was a simple and smart model that was built using the concept of distance map (Xie & Li, 2014). The advantage of the Cellular Automata model was the features of avoiding obstacles and calculating the shortest path to handle the evacuation simulation efficiently. The disadvantage of the model was that the distance map concept only defined a two-dimensional grid cell. The distance calculated cannot be used for a multi-floor building. The distance map concept was one of the basic theories of a indoor navigation system. The programming language was usually Visual Studio C++ for this Cellular Automata model. Since C++ language doesn’t have the automatic memory allocation for stack handling, the author of this thesis recommends Java for programming purpose.

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, Zheng, Villalobos, & & Gautam, 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.

The simulation can be compared with the observable data such as the surveillance video for crowd behaviors to check the accuracy of a model (Ballan, Bertini, De Bimbi, Seidenari, & Serra, 2011). People can validate the simulations of evacuations under normal conditions using the data related to the normal evacuations. But in case of emergency, it's hard to validate due to the lack of knowledge of the unpredictable variables. Therefore researchers have been trying to design hybrid simulation models for evacuation simulations. For example, the real-time feeds from the surveillance footages are monitored to investigate the behavior dynamic for the simulations. (Tissera, Printista, & Luque, 2012). It is also possible to include the social and psychological factors of the evacuees into the models. Agents were profiled with various human behaviors according to the variables of the state of mind such as anger, happy, fear, etc. More discussion of those agents are included in Chapter 7 for recommendations and future work.

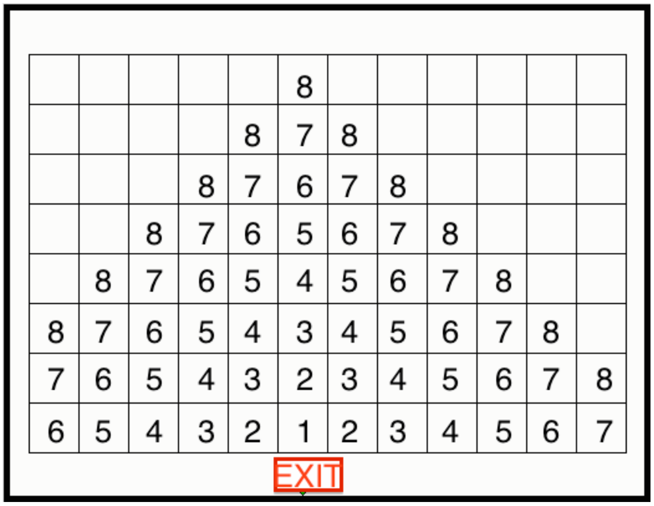
Almeida and colleagues implemented multi-agent system model in evacuation simulations using the Beliefs, Desires, Intention (BDI) techniques (Almeida, Rosseti, & Coelho, 2013). The model calculated the profiles of the agents according to the social behaviors of human beings. BDI is where agents are capable of fulfilling the desires according to the beliefs (i.e. set of rules and knowledge) and intentions (or actions). It means calculating the functions of how to leave the place from where they are, using the shortest path and taking necessary actions programs the behaviors of agents. The agents' attributes are profiled according to the some social related factors, such as knowledge and experience. The attributes also depend on gender, age, vision and other personal factors. A Computer Fluid Dynamic (CFD) model, such as the Fire Dynamic Simulator (FDS), will define the interaction between the environment and the agent. FDS is developed by the National Institute of Standards and Technology to build a fire evacuation environment in a simulation. The same technology could be used to develop other environmental behavior simulators for various emergencies.

The 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.

Algorithms and Theories

The essence of an evacuation route is the calculation of the shortest path to the nearest exit and the computed route should generate less crowd density. The well-known Dijkstra's algorithm will be used to compute the shortest path to the nearest exits in this thesis. The shortest paths will be computed according to the locations of nodes. The basic theory behind an evacuation algorithm is to divide a complex area into sub parts (or cells) virtually (Xie & Li, 2014), which are time steps. See Figure 2 for the explanation of time steps. A time steps ticks an evacuee's move of one step from his or her stay on the start position to all the surrounding possible next position (Xie & Li, 2014). This algorithm was called distance map (Xie & Li, 2014). A distance map can be used to understand the 2 dimensional graphical view of the shortest path and the 3 dimensional graphical representation of the shortest path. The limited space, the different layouts of buildings, and the unpredictable behaviors of the evacuees cause the complexities in simulations. The distance map algorithms locate the evacuees and provide routes for them to go to the nearest exits.

Figure 2 shows a simple grid view of the calculation of the shortest path to an exit. The capacity of the exit is one egress. Therefore the example model demonstrates the evacuation of one person at a time. Each time the steps that an evacuee moves to the exit direction will be one cell. In this example the movement follows the least number of steps in each route. If there is an obstacle, it follows the next least number of steps in the grid. This basic concept of calculating shortest path is implemented in most of the software of modern evacuation simulation. The advanced version of the program has been introduced in the Pedestrian Dynamics (PD) evacuation simulation software to calibrate a smooth flow of evacuation using global route algorithms (GR) (a.k.a. Shortest Path) and indicative route method (IRM), which is capable of managing the broad range path, avoiding obstacles, and computing smooth path (INCONTROL, 2014).

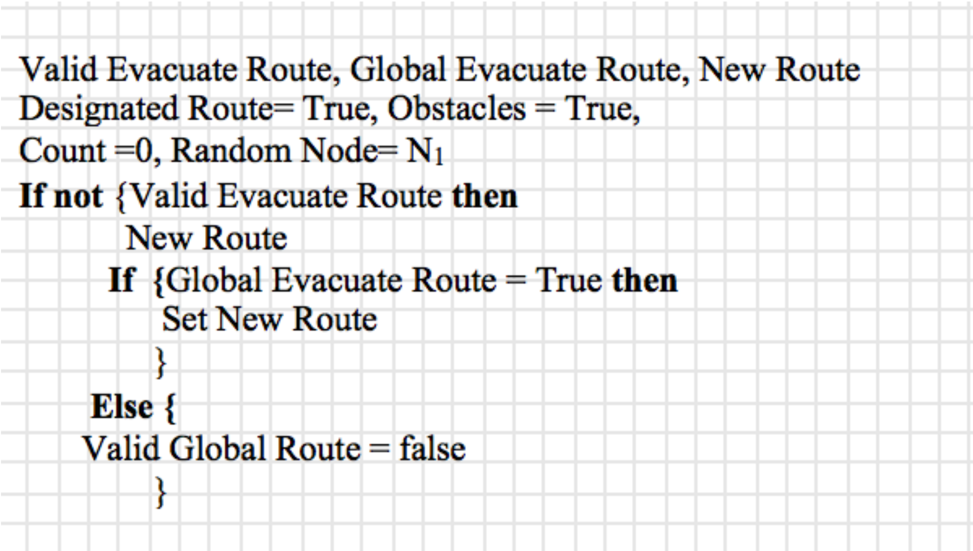


					8						
				8	7	8					
			8	7	6	7	8				
		8	7	6	5	6	7	8			
	8	7	6	5	4	5	6	7	8		
8	7	6	5	4	3	4	5	6	7	8	
7	6	5	4	3	2	3	4	5	6	7	8
6	5	4	3	2	1	2	3	4	5	6	7

Figure 2: Example Grid View for Calculating the Shortest Path

Cognitive science approach was introduced to create a realistic spread of crowd flow. This method is based on the vision and the behavioral heuristics. The method applies line of sight, visual information, and obstacles details to pedestrian walking speed and directions to calibrate the action of the avoidance of obstacles and create a smooth flow of evacuation. Navigation technology creates a choice to avoid obstacles, which gives a clear view of the in-door geometry.

The development of an algorithm needs to consider every definable factor in a particular environment. Even though Dijkstra algorithm calculates the shortest path, it cannot define some advanced evacuation routes with shortest paths in the real world. Such a system needs to have the capability to run multiple algorithms concurrently to identify the best route for the situations in the real world. Multi-agent simulation should have the capability to generate various agents with different behaviors for the diverse situations. The algorithms identify the indoor geometry and generate nodes automatically for every location. If there are no obstacles between nodes, the location nodes are connected. Figure 3 shows the algorithm of how to guide an agent through a suggested evacuation route.



```
Valid Evacuate Route, Global Evacuate Route, New Route
Designated Route= True, Obstacles = True,
Count =0, Random Node= $N_1$
If not {Valid Evacuate Route then
           New Route
         If  {Global Evacuate Route = True then
               Set New Route
               }
        Else {
      Valid Global Route = false
               }
```

Figure 3: Computing Algorithm of a Sample Route

BIM for Large Structures

Building Information Modeling (BIM) technology furnishes a digital and integrated representation of the actual physical characteristics of a building. It is used in computer-based fabrications and to share knowledge for resources utilization, design optimization, technology innovation, and process breakthrough and operations transformation purposes. When industries deal with large structures, sharing information is critical to manage projects. In order to run large-scale projects successfully, information should be shared among designers, constructors, and operators. Presently, BIM platform introduces the reliable and effective functions for the productive communication technologies between departments for construction projects. It is a centralized system. BIM improves communication and the operational efficiency. It cuts down the time for cross-referencing review and approval. It leads to high productivity and reduced cost. BIM decreases major reworks of a project (Ahankoob, Khoshnava, Rostami, & Preece, 2012). Unclear information between the departments of a project is corrected and updated. As a benefit of BIM, most fabrications can be modeled, documented and manufactured off site. BIM can provide documents with improved quality, which are the most related parts to evacuation plans. Infrastructural designers document 2D and 3D drawing and drafts, with all the information of projects. These 2D and 3D drawings are be used to identify and define the evacuation routes. Evacuation simulators can use BIM models as simulation environment. For example, Revit models and Tekla models can be used as imports to the software. Evacuation plan could also be a part of BIM. As a centralized platform, BIM also add the safety performance into the system. The evacuation and safety measures could be calculated and arranged before a project is done.

BIM provides a perfect platform for sharing the information. It is critical for large-scale emergencies. Stadiums are capable of seating a large number of crowds. Their evacuation plans should be capable of evacuating a large scale of crowd in the least amount of time. BIM provides comprehensive building information for visualizations of the interior design of the stadiums, which helps to build a productive evacuation simulation. Well-defined information will be gathered by the BIM platform to define the basic safety measurements. The information will be used to identify the real details of the exit route, exit doors, and the seat layout of the stadiums. The information can also be used to compute the capacity, distance, average evacuation time of the exit routes, and the number of doors. In order to manage the crowd in a stadium, interior designers should consider the safety measurements. Managing crowd means to divide the seats into sections and manage the access to the section. Many interior designs of stadiums are symmetric in layouts. This type of layouts helps to provide the balanced crowd evacuation from each side of a stadium. In order to avoid crowd bottleneck, the seats in each section are also managed to have the same capacity.

The approach to develop an evacuation plan for a stadium depends on the features of the BIM platform. Using the visualization methods, safety management can deploy the proper evacuation plans for the facilities. Observing real-time human behaviors in an emergent situation should validate evacuation simulation. It is almost impossible to validate. BIM plays a significant role of providing real-time and accurate building information in an emergency. But the lack of studies is a major issue to embed the human behavior modeling into simulation models (Wang , Li , Rezgui, Bradley, & Ong, 2014).

Emergency management of a building is a major part of its life-cycle process. The emergency plans will be activated in response to particular onsite incidents. It reacts to real-time human behaviors and facilitates timely information for communications. To prepare for urgent situations, the common approach is to execute emergency drills following an emergency plan. The new approach using BIM-based simulations is a major breakthrough of the industry. It saves money and time (Wang , Li , Rezgui, Bradley, & Ong, 2014). Computer-based evacuation simulations enable people to utilize databases and file systems to explore the human behaviors during evacuations. In this research, the author used a revised Pedestrian Dynamics system to study human behaviors with file systems following Dijstra and Open Cleared Path algorithm, during evacuations in the virtual BIM model of Hancock Stadium.

BIM-based simulations have a number of advanced features, such as integrity analysis and the behavior predictions of occupants. Model driven (MD) architecture and the Restful Interoperability Simulation Environment (RISE) provide the framework for the BIM-based simulations. Industry Foundation Classes (IFC) enables the interoperability of BIM data. Many BIM platforms use IFC to transfer models. For example, Autodesk Revit, Autodesk 3D Max, Bentley Architecture and Graphisoft ArchiCAD are all using IFC and its domains to enable the interoperability among BIM models (Wang, Gabriel, Goldstein, & Khan, 2013). Because of the implementation of IFC in BIM software, almost all files can be imported to any BIM software. Evacuation simulations need to have 3D visualizations to check the safety performance of the designs. New evacuation simulation software with BIM functions has been introduced to the market. The new systems have the following features: (1) they depend on IFC. (2) Any file of BIM can import to the software. (3) 3D visualization and advanced evacuation features have been implemented. (4) They can identify the shortest paths and possible exit doors automatically without manual definition. (5) They have the modes of active and passive collision avoidances. (6) They use agent profiling and dramatic human-behavior profiling.

Safety Issues in Large Crowd Areas

Handling a large number of crowds in a limited area is critical and essential for the safety of people. Especially the places, where a large number of crowds get together such as stadiums and arenas, should have proper plans to avoid the catastrophic incidents in case of emergencies. The plan should focus on the evacuation of everyone within safety time fame and without damaging properties (or with a minimum damage). Every possible onset event of emergency has to be defined. The evacuation scenarios should be implemented. The scenarios for fire and for tornado are different and their variables vary as well. Issues have been found where a large number of crowds get together where the limited access routes and exit doors. This thesis will highlight some of the issues by categorizing them to technical, sociological, physical, and resources aspects.

Even though safety management is essential for the most commercial buildings, the lack of studies and resources decreases the development of the evacuation technology. One of the major reasons of the lack of studies is the difficulty to define the variables and evacuation situations. Defining the variables is extremely critical. But their accuracy of the predictions is not hundred-percent correct. High uncertainty is the hurdle in the path of searching for the best evacuation plan in case of emergency. The optimization of the possible evacuation scenarios includes using proper algorithms to generate a productive evacuation plan. Emergency situations happen randomly. It's important to hire a safety expert and use his knowledge to prepare for emergencies in large events.

Stadiums and arenas have designated access routes and exits. Problems may happen when there is limited space at evacuation routes and exits comparing to the number of people in the crowd. When the number of evacuees is beyond the capacity of the limited space of the exits, it causes crowd bottlenecks. It's difficult to predict where a crowd bottleneck may occur. But the bottleneck must be handled before it happens. The layout of a facility, such as a stadium, influences the judgments of crowd and may lead to crowd panic in case of an emergency, particularly when the open visibility of a person is affected in the facility. Changing indoor-layout of a facility may prevent crowd bottleneck. . In a facility when a large number of crowds start to gather at a spot, it is the time to broadcast the proper navigation system to guide the people to the nearest exits safely. Currently, there is no effective system or technology that can be used at every building or a proper device to either send or collect the information to or from evacuees.

The sociological issues in large-scale emergencies are the most vulnerable matters for safety managers. It's complicated to determine the psychological situation of the whole crowd. People tend to panic when they see an incident and try to escape from the hazard as soon as possible. It's a natural reaction of a human being to get away from any life-threatening situation. The reaction is different from each other. It's hard to believe that everyone follows the same rules in case of emergencies, let alone that everyone has the awareness of evacuation procedures. The characteristics of social vulnerability include age, gender, class, people with disabilities, and education. Yet, the various characteristics in evacuation situations and simulations are not developed in virtual agents of the simulation systems. The virtual agents don't have categories according to those aspects. Children and adults with disabilities in a large crowd need to have guardians to guide them to evacuate out of the premises. One issue in computer simulations is to profile agents with weaknesses. The situations make the safety management complex.

Stadiums should be fully equipped with the Closed-Circuit Television (CCTV), fire sensors and other safety devices in order to provide complete safety service to minimize damage in case of emergency. Electricity must be supplied continuously. Even though almost all stadiums are capable of providing safety service, these are no guarantee that all the technological devices will be functioning in case of emergencies. Since the tech-devices are powered by electricity, their services may not be available in case of the break -down of the power supply in emergencies, such as earthquakes, tornado, and fire. It is hard to manage a large crowd manually by human. This emergency management depends on technology when developing evacuation scenarios; experts have to design the plans under some critical assumptions.

Comparison of Simulation Software

Powerful crowd-simulation software has been introduced in the past couple of years. The author compared the following simulation software in the study: Massive Prime, An(i)ma Axyz, Golaem Crowd Generator, Miarmy, Legion, CrowdFX, Pedestrian Dynamics, 3Ds Max Populate, which are the most powerful simulation software in the market today (VFX, 2015). Massive Prime has been rated as one of best simulation software in the market, but its primary usage is simulating graphic effects for movies and games. It also has the engineering applications for emergency evacuations, which provide accurate imitation of motion and behavior. It is also capable of generating agent-based, unique, artificial intelligence technology. On the aspect of cost, the product is expensive (VFX, 2015).

An(i)ma is for architectural visualizations. It's the cheapest, performance-cost-balanced software in the market. It works through a plug-in for Autodesk 3Ds Max, which is leading 3D modeling software in the market. The software is capable of proving advanced features of crowd simulation, such as crowd cloning and collision handling. Its most important capability is importing other BIM files (AXYZ, 2015). The populate tool of Autodesk 3Ds Max is an inbuilt simulation feature. It has crowd behavior options as well. But the populate tool doesn't have the advanced features of agent profiling or agent dynamics based on artificial intelligence. It impersonates crowd movement in a single floor area. Some real-time features, such as stair climbing behavior, cannot be generated in the populate tool.

Miarmy and Golaem are animation engine plug-ins, which are capable of creating realistic crowd behaviors for Maya animations software. They are not specifically made for the usage of crowd evacuation simulation. Even though they have graphical capabilities, they do not simulate real-time evacuations in emergencies. Both plug-ins are not for safety evacuations. One major weakness of Miarmy is that it is incapable of handling more than 100 characteristics at once. It cannot simulate a large crowd evacuation. The main advantage of it is that it can generate agents with much advanced behaviors.

Crowd FX, Legion EVAC (or Legion), and PD are the most productive and user-friendly software for the crowd simulations comparing to the aforementioned ones. Crowd FX is capable of generating Interactive Creative Environment (ICE) nodes for crowd simulation, in which, the agents can follow an intelligent navigation process. It also has the advanced features such as collision avoidance and agent profiling. As an Autodesk product, Crowd FX gives can import and export the files with other BIM software. Legion is for operation safety with crowd visualization and security assessment. Legion is capable of providing advance crowd movement features which can be plugged into Autodesk 3ds Max. Legions is capable of simulation and analysis to provide statistical data for decision-making support. It is also compatible with National Institute of Standards and Technology ’s (NIST) Fire Dynamic Software (FDS).

Pedestrian Dynamic (PD) is ideal for the simulation of emergency evacuation because it has functional features to generate a real-time evacuation simulation. It satisfies technical requirements by the demands of safety authorities. It can generate crowd flows, predict bottlenecks and imitate real-time agent behaviors. It is capable of developing different emergency scenarios and evaluating mobility of the evacuation scenarios and infrastructure plans of the facility (Barrett, Beckman, Channakeshava, Huang, Kumar, & Marathe, 2010). This software is for evacuation simulation inside the facilities such as stadiums, airports, stations, etc. where large crowds interact. (INCONTROL, 2015). PD is able to calculate simulations of large crowds up to 100,000 persons. It can import industry standards in various formats, such as CAD, XML, and

CityGML. It provides explicit corridor mapping, microscopic and macroscopic simulations (INCONTROL, 2014). In this research, PD software was chosen because it offered fully functional, free trial version. It made the research possible to study the details of simulations with a full functional version of PD. PD software meets the high-level expectations of industrial needs. But the software itself is the most expensive one in the field of emergency simulation.

Table 2.1 is the comparison of the functions, advantages, disadvantages, and applicable areas of the aforesaid software products. Based on the comparison, the author chose In Control Pedestrian Dynamics to develop the simulation for the Hancock Stadium at ISU.

Table 1: Comparison of Simulation Software

Name	Especially designed for crowd simulations	Price	Technical knowledge needed	Standard CAD supports
Massive Prime	NO	Medium-High	Moderate	NO
an(i)ma® axyz	YES	Low	High	YES
CrowdFX	YES	Medium	Low	YES
PEDESTRIAN DYNAMICS	YES	Expensive	High	YES
Legion	YES	Medium	Moderate	YES

Case Studies

Philips Stadion Soccer Stadium Case Study

Philips Stadium has the capacity to host 35,000 soccer fans (Stadiums, 2015) in an event. The safety management, especially evacuation plans, of the stadium was optimized using simulation software. PD was introduced as a simulation tool for the solution of complex safety management in the stadium. It included every scenario of the possible or imaginable emergencies and regular evacuations. Figure 4 shows the CAD model of Philips Stadion Stadium.

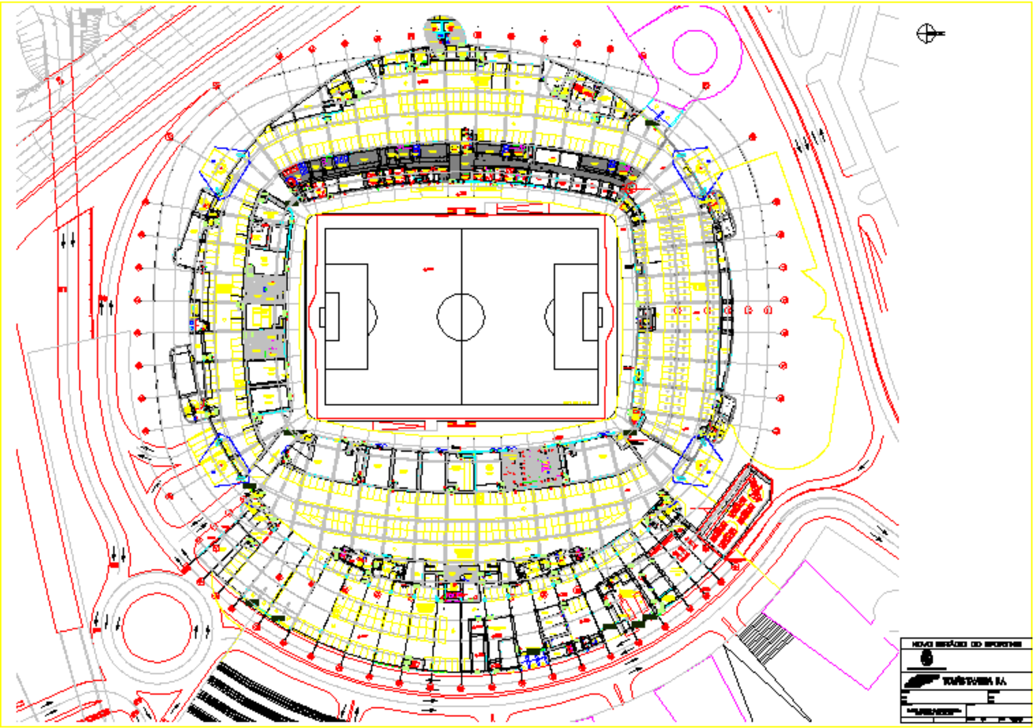


Figure 4: CAD Model of Philips Stadion Soccer Stadium (Source: http://www.bibliocad.com/library/stadium-plan_67932)

After the validation of the exits and access routes of the stadium, evacuation parameters were designed using the PD of the stadium. Crowd flows; bottlenecks, and risks were simulated during different evacuation scenarios. From the analysis of the data, people can find out how the crowds respond to different evacuation scenarios in the stadium and where the crowd bottleneck occurs.

University of Southern Mississippi Football Stadium Case Study

Geographic Information System (GIS) based, macro-simulation was introduced to calculate the evacuation time of the Football Stadium of University of Southern Mississippi (Kar & Zale). The stadium is capable of providing 33,000 of seats for sport fans. There are 16 exit doors and emergency exits, which allow 25 persons to exit per second from each door according to the calculations. Simulations were calculated for the total evacuation times for different evacuation scenarios of emergencies and regular situations. Normal walking speed of a human being is 1.5 meters per second (Hoogendoorn & Daamen, 2003). If the evacuation is smooth the stadium could be evacuated in 200 seconds in an ideal situation. The simulation software used to build the simulations was with high profile, which is not available to the public use. The GIS-based platform is currently used only for military and government needs.

CHAPTER III

METHODOLOGY

The proposed approach to develop an evacuation route would produce optimal solutions based on the simulation results for proper evacuation plans. The models and simulations were categorized based on the number of evacuees. Particularly, there are 1000EVAC, 2500EVAC, and 7500EVAC respectively, for the audience groups of 1,000; 2,500; 7500, people. Each simulation generated a different evacuation process, which was best for that situation. Dijkstra's algorithm was used to find the shortest path to an exit. The open-cleared-path-first algorithm was used to execute crowd control with minimum bottleneck in the shortest path. Combination of those two algorithms would generate a possible evacuation path with shortest travel time.

According to the aforementioned algorithms, the access routes of Hancock Stadium would be detoured to the recommended paths. Any of the recommended paths composed the movement in 3 directions, which are X, Y, and Z-axes of a space coordinate system. The stages and steps that the bleachers attached to in the stadium caused the 3-directional movements. Figure 5 shows the section detail and structural design of the stadium. Moving characteristics of the vertical and horizontal evacuation may be changed in each simulation. For the simulation purpose in this research, the crowd was grouped according to their seats.

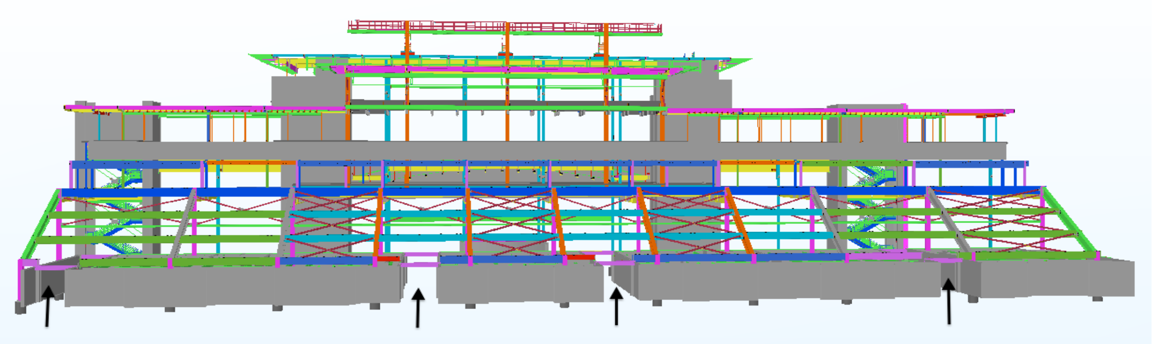


Figure 5: North Pavilion

Figure 6 shows the general seating groups of the stadium. The seats were divided in to subgroups for the evacuation plan. The simulation results were compared with the regular evacuation. The detailed discussion of the results of this comparison is included in Chapter IV. If the results match, the proposed evacuation model and the simulation could be used in a real time scenario.

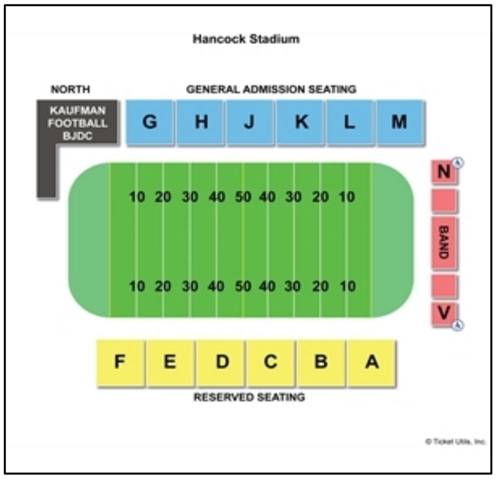


Figure 6: Hancock Stadium Seat Layout (Source: Illinois State University)

Materials, Equipment, and Procedure

The modeling and simulation of the evacuation plan for Hancock Stadium have three major tasks, which are: (1) building the simulation, (2) collecting video surveillance of events, and (3) comparing and validating the simulation with real-time data. The simulation needs simulation modeling software and high performance computers. The hardware configuration of the computer used in this research included core i7 processor, 16 GB RAM and NVidia graphics processing unit. The floor plan and the 3D drawing of the Hancock stadium were needed for the information of the building measurements. Seat layout graphs were also helpful to divide the crowd into groups.

In the second phase of the research, site data were collected to analyze the real crowd behavior. The video footages of several events were analyzed for the crowd behavior in regular evacuations. A digital storage drive and a computer with10GB hard drive were used to store the video files of the evacuation.

In the final phase of the research, the author compared the differences between crowd simulations and proposed suggestions for the emergency evacuations in Hancock Stadium. In this research, the author used Pedestrian Dynamic software for crowd analysis.

A major task of the project was to calculate TET (Total Evacuate Time) for each evacuation scenario. The simulation software calculated the capacity of the exits, crowd density, TET, and Shortest Cleared Path (SCP). The calculations of TETs and crowd densities of real situations were critical and were done manually. The precision of the calculation of density was set to 10 seconds in time frames. The first time frame started when the first person evacuated from an exit. To calculate the SCP for the crowd from real emergency situations, the author used the same movements of the crowd in regular conditions. Pedestrian Dynamics software automatically generated the calculations for Tx (Time take to reach to an exit), Cx (Capacity of exits), Vx (Volume of the crowd in an exit), and SCP (Shortest Cleared Path) for every phase of the project.

The final phase of the research was to validate the evacuation scenarios according to the real situations. The author identified and validated the crowd movements, response time, total evacuation time, and crowd bottleneck behaviors in the simulations. The author also downloaded and imported the real-time videos to the crowd analyzing software to get the different levels of details of crowd behaviors using microscopic and macroscopic approaches. The simulation of evacuations automatically generated the detailed reports of the evacuations. The author then performed the task to identify the differences between the simulation reports and the reports from real situations. Although the average response time and the total evacuation time could be validated according to real records, the validations of the exact crowd-behavior patterns and the locations where the crowd bottlenecks occur remain a challenge.

Data Collection

The major data for the project was a collection of surveillance video footages from Hancock Stadium. Since the study focused on evacuation, the video footage with the records of how people are being evacuated from the facility in special events were collected. (i.e. home coming and major football games). Since the stadium did not have a history of emergencies, video footage of emergencies were collected from published sources. According to the published sources, most of stadium disasters happened due to crowd crush or pile ups (Lee & Hughes, 2005). The video resources were difficult to collect when stadiums were in fires or other emergency situations.

Several types of data were collected from the video footage for analysis. The details of the crowd behaviors, such as where the crowd bottleneck occurs, were collected using microscopic and macroscopic graphs. It was hard to measure the density of the crowd from with the bare eye. The author used the microscopic and macroscopic graphs to identify the crowd patterns and the density of the crowd. The average response time was collected for the further development of the evacuation plan. The average TET was calculated to validate the simulation scenario of evacuations in regular situations.

The author collected data through an onsite survey about how long it took a regular person to vacate from one random seat in Hancock Stadium in different ideal conditions. In this research, the ideal conditions meant that an individual was able to move freely without any crowd interactions. According to the collected data, the author discovered that an individual could vacate the stadium between15 and 97 seconds with no crowd interaction. Table 3.1 shows the sample data collected from the survey.

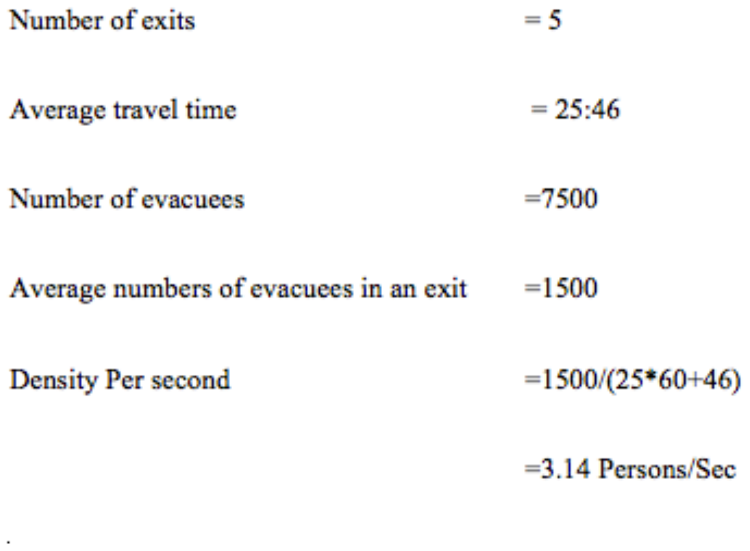
Table 2: Observed Evacuation Time from a Randomly Selected Seat

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

The data were collected three times for each situation in the survey. 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.

Calculation Methods

The calculations on the collected data through observations and the simulation results are to generate the TET (Total Evacuation Time) for every scenario. 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. Figure 7 shows 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 =7500

Average numbers of evacuees in an exit =1500

Density Per second =1500/(25*60+46)

=3.14 Persons/Sec

Figure 7: Example of Density Calculation

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 observation 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 permanent 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.

CHAPTER IV

SYSTEM DESIGN AND RESULTS ANALYSIS

System Design

The flow chart in Figure 8 shows the design of the simulation system. The first step was to identify the numbers of occupant in the stadium. The author categorized them into three groups according to the number of occupants (1000, 2500 and 4500). When the number of evacuees is getting higher, it is riskier to form up certain hazardous conditions in the facility. The above numbers were selected to provide the good understanding of the mass behaviors in a large-crowd-evacuation process. The next step was to check whether the data was from a real time observation or a simulation. The simulation results were automatically generated after the simulation was done. But the video files had to be analyzed manually. The next step was to select the cause of the evacuation, which could be an emergency or a regular evacuation. If it is an emergency evacuation, the reason of the evacuation should be provided. After that, the system got the data when a random exit was blocked. The final part of the research was to obtain the data and generate reports.

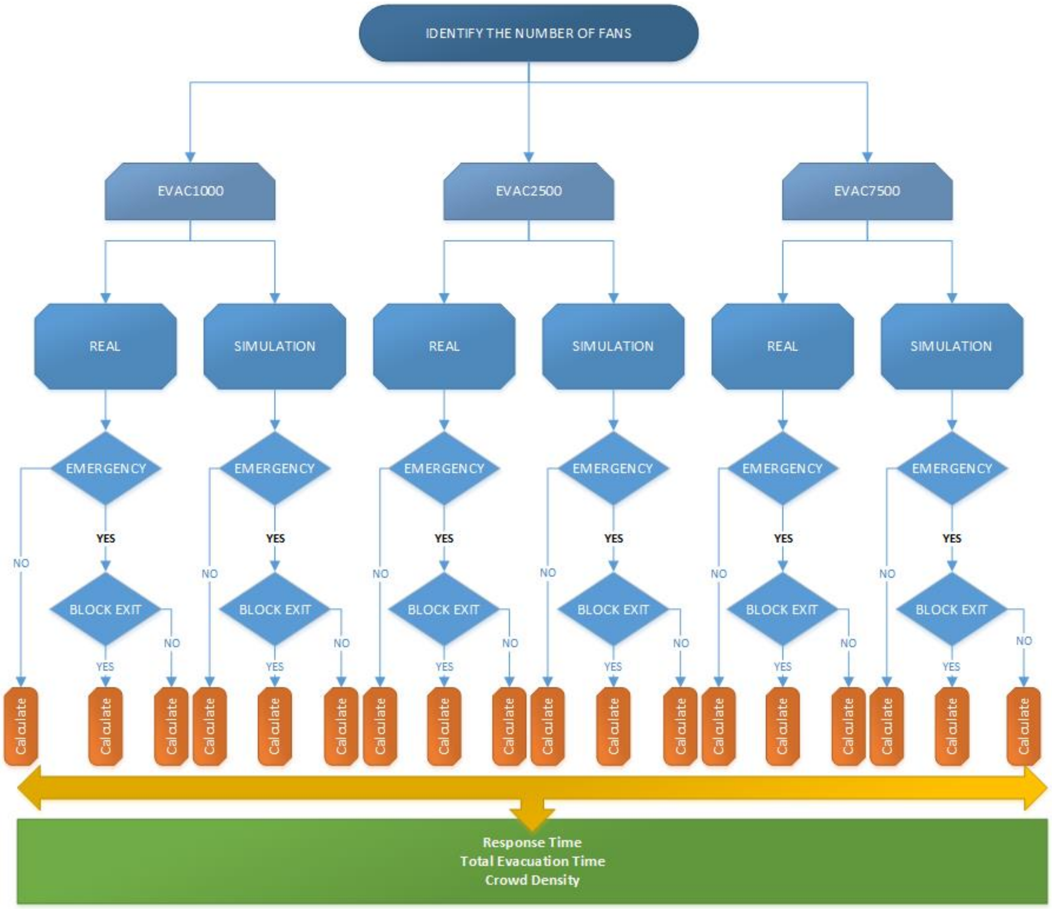


Figure 8: Design of the Simulation System

Results Analysis

The numbers of calibration plots show the dynamics of the crowd behaviors in the stadium. It is important to find out the crowd density of a location during an evacuation. The places near exits have higher density than any other places in the stadium. So the author measured the crowd densities over time near the exit areas to analyze the risk factor of crowd bottleneck. Figure 9 shows a calibration plot of how many agents per one square meter over time near a specified exit area.

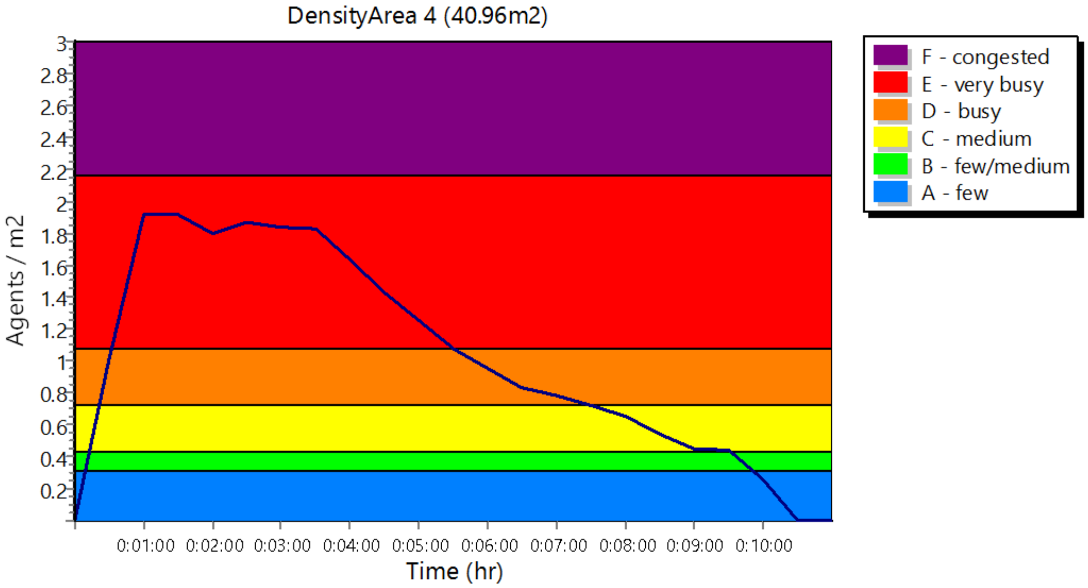


Figure 9: Density of an Exit during an Evacuation

One of the major objectives of this research is to calculate the total evacuation time of each evacuation scenario. Optimizing the data from each evacuation scenario can produce better opportunities to obtain accurate data. It is important to have the records of how total evacuation time varies over the numbers of evacuees. The calibration plots in Figure 10 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.

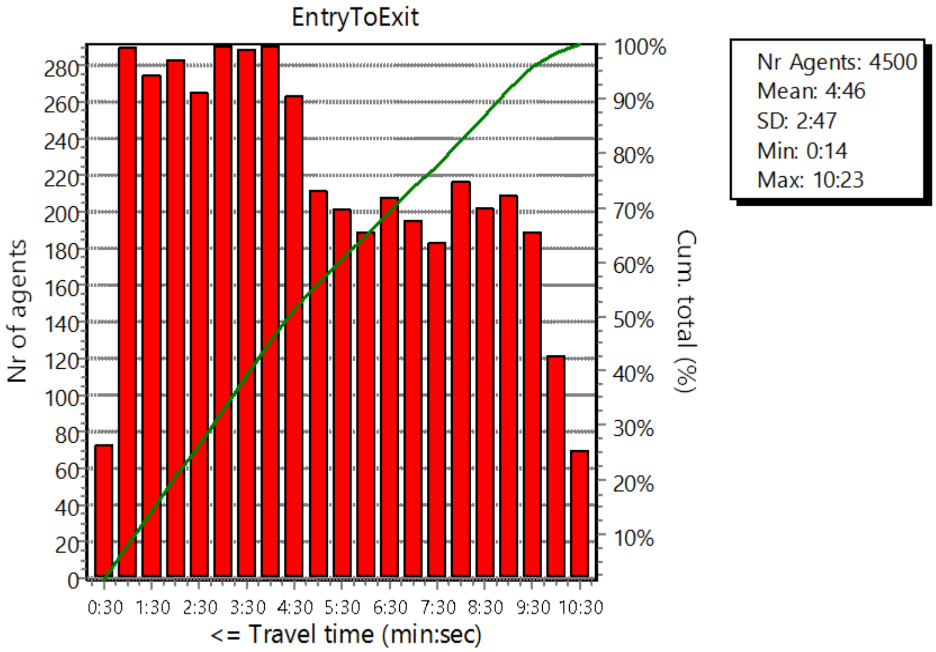


Figure 10: Evacuation Behaviors of Agents

The author 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 11 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, how many people move across the line to one direction and how many people 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, which is the direction to go out of the facility. The calibration plots in Figure 11 shows the crowd behaviors when moving toward the direction of exits during evacuation.

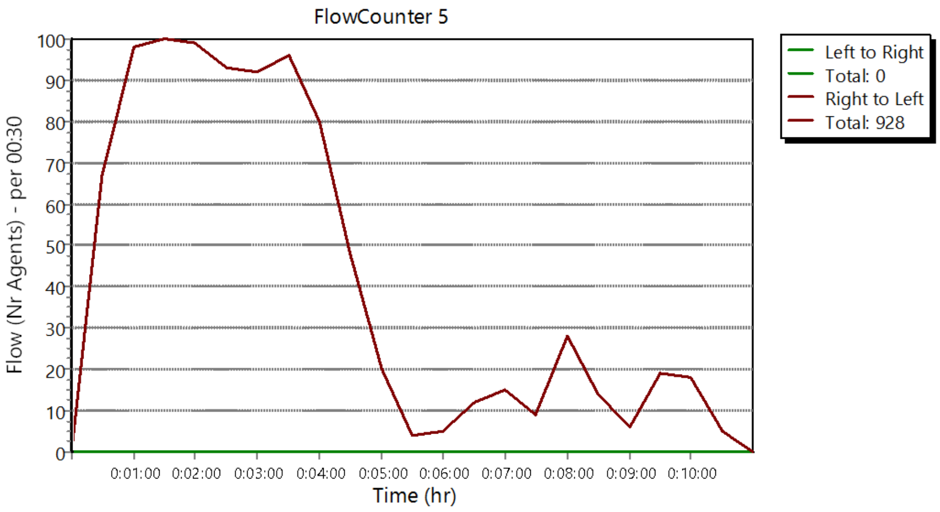


Chart 5: Flow counter per time interval

Figure 11: Number of Agents Moving Across a Specific Place

The Hancock stadium evacuation simulations have generated numeric important result for researchers to analyze and enhance the safety of the facility. Results from 3 main scenarios indicate that the TET varies from 4:45 minutes to 20:20 minutes based on number of evacuees. Figure 12 shows the results in 1000 EVAC scenario. The results show that 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. Comparing to the ideal situation, in reality, an individual takes almost more than 80 seconds to vacate the building.

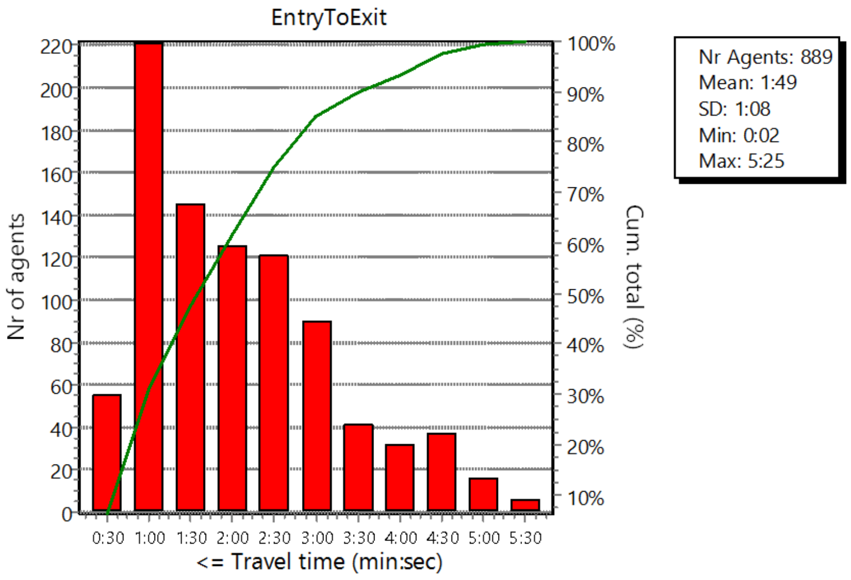


Figure 12: Evacuation Behavior in 1000EVAC

Another sub scenario is to analyze 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.

Readings are getting more critical near the exits, where the exit routes are busier than in other scenarios. According to the readings, the TET for 2500EVAC scenario is 9:18 minutes. The mean of the TET is 3:24 minutes. The average evacuation time is 4:46 minutes in the main scenario of 2500EVAC. Figure 13 shows the behaviors of the crowd over time. It’s interesting that nearly 50% of the crowd evacuate during the second and third minutes of the evacuation. There are more than 200 people evacuating during the second minute of the evacuation process. Figure 14 shows the density of some exits during evacuations. It shows how serious the crowd bottlenecks at random exits are in 2500EVAC scenarios.

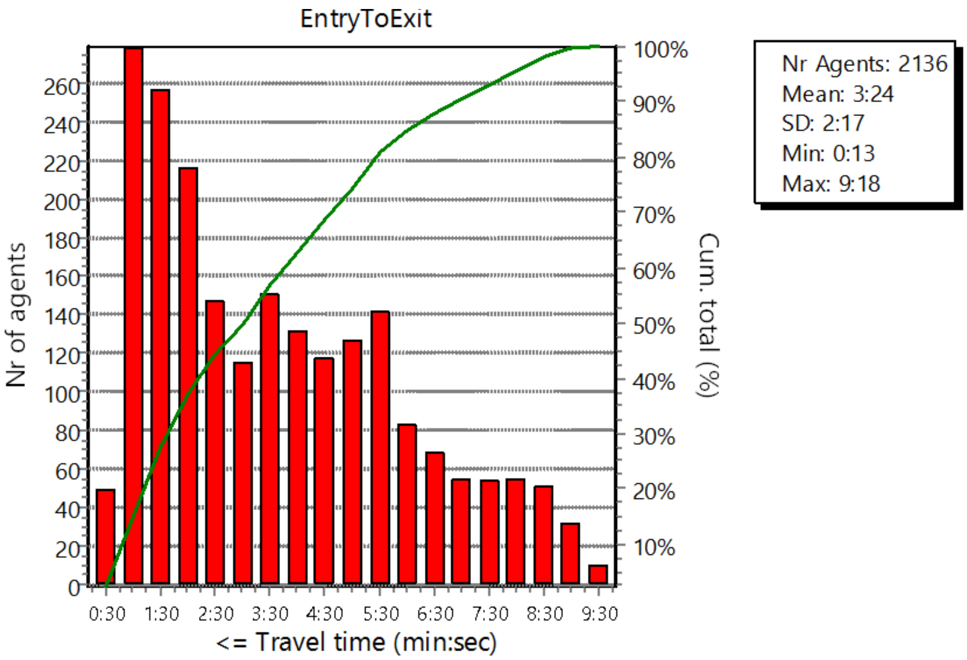
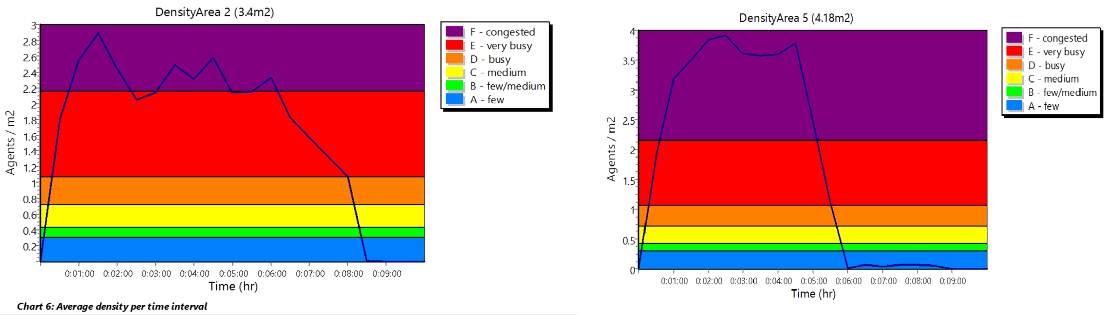


Figure 13: Evacuation Behaviors in 2500EVAC

The stairs near the exits are congested between 2nd minute and 6th minute of the evacuation process. The average density of the exits is 3.6 persons per square meter during that period of the evacuation, which creates a potentially hazardous condition on the stand. The two exits doors are the west corner exit and center east exit of the stadium. According to the graphs that the west corner exit is congested more times than the center east exit but the density is higher than the west corner exit.



West Exit Center-East Exit

Figure 14: Density of Exits

Figure 15 explains the density scenarios. It shows how the density varies from one location to another. It is clear that the exits are congested and evacuation routes are busy according to the 2D evaluation screenshot of the stadium in the simulation system. The bottom rows of the bleachers are the most important areas during evacuations because the crowd-flow always moves down to those areas during evacuations. The stairs between access route and the stand, which has the main access to the major exits, have the potential of getting congested during the evacuation processes due to the layout of the stadium.

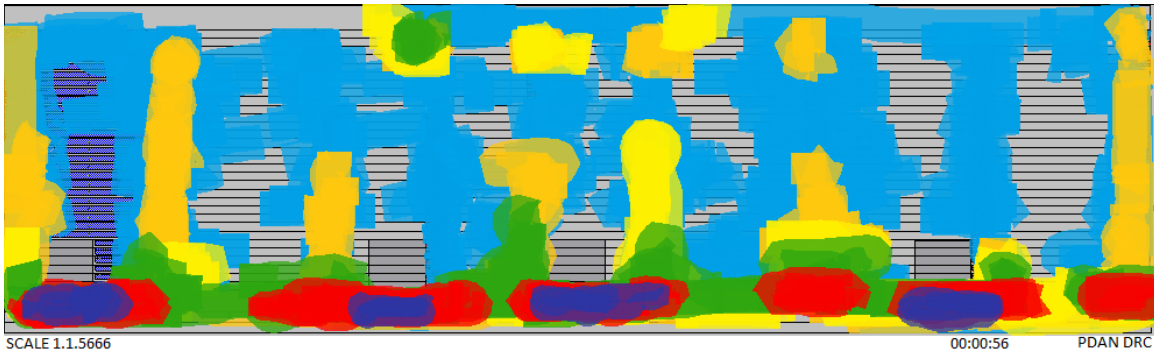


Figure 15: Density of the Crowd During the Evacuation

There are nine access stairs to the stand, which could make a potential crowd bottleneck during an emergency evacuation. An interesting crowd pattern develops when the crowd starts moving in the members' area of the stadium. The members are located at the upper center of the stadium. At the beginning of an evacuation process, they should move upward to get to an access stair and move down to get to the exits. According to the survey this area takes the longest evacuation time in ideal conditions. When the center-west exit gets blocked in the sub-scenario of 2500EVAC, the total evacuation time rises to 9:28 minutes, which is just 10 seconds more than the regular evacuation time.

It is always critical and challenging when evacuating a full stadium. The capacity of the main pavilion of Hancock Stadium is up to 7500 individuals. The audience may reach to the full capacity of the stadium in events such as homecoming. Unlike other scenarios, in the 7500EVAC, there are more interacts of crowd and exits routes. The doors are more congested than other scenarios. The 7500EVAC scenario takes 20:20 minutes to perform a full evacuation, which is twice longer than the TET of the 2500 EVAC scenario. According to the graph in Figure 16, the TET increases rapidly with the growth of the number of evacuees.

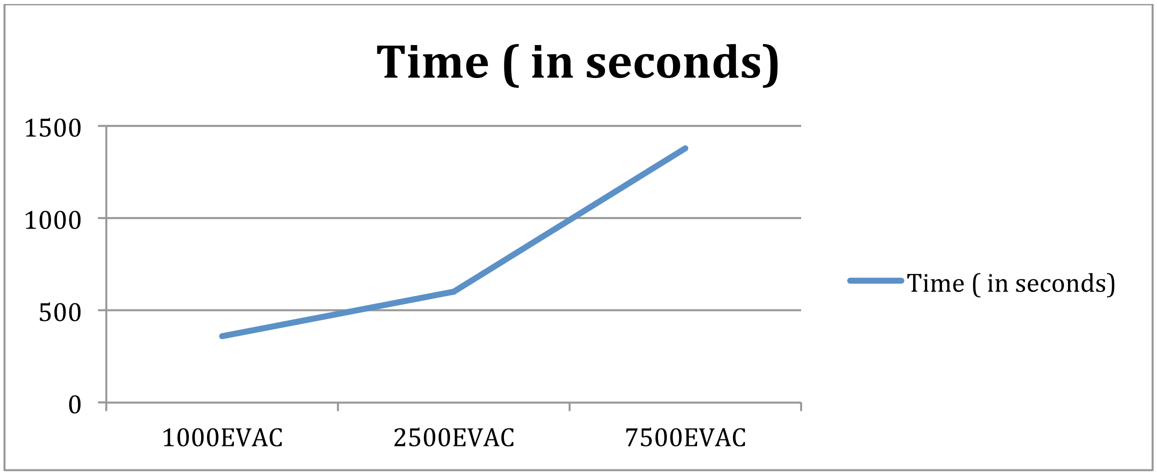


Figure 16: TET of Evacuation Scenarios

When the numbers of evacuee are high, it takes much time to evacuate people due to the limited spaces in evacuation routes. Figure 17 shows the crowd densities of two random locations in the stadium where they could be congested during evacuations.

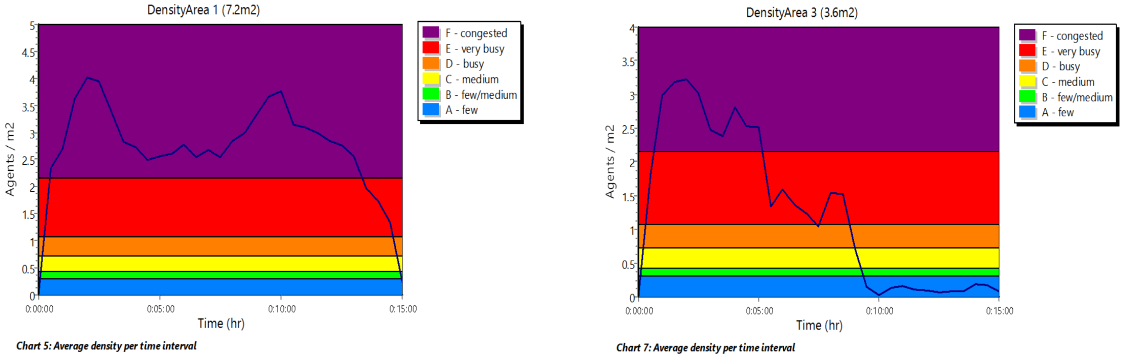


Figure 17: Crowd Density Dynamics of Two Random Locations

According to the results, the crowd is congested during the first 15 minutes of the evacuation when accessing the stairs to the exits. The average density of those locations is around 2.5 evacuees per square meter. Figure 18 describes the flow count of two different places of the stadium.

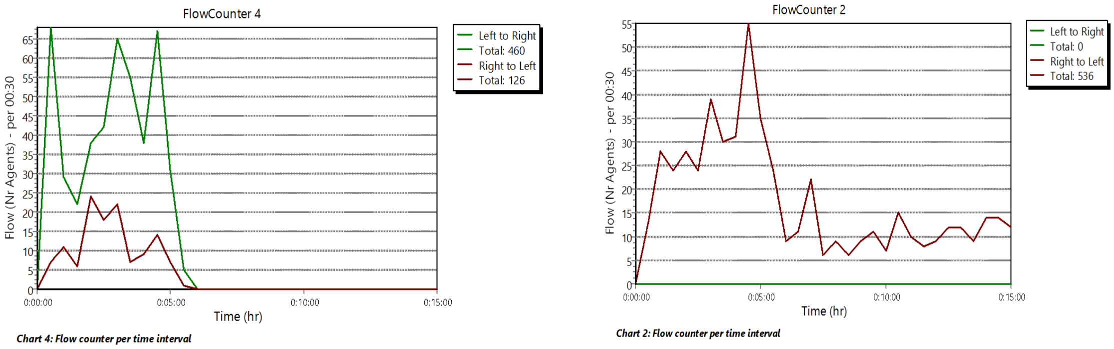


Figure 18: Flow Counts of Two Different Places of the Stadium

The first graph of Figure 18 shows the flow counts near the access stairs and the second graph describes the flow counts of one of a main stairs. According to the first graph, evacuees are moving in two directions to find the exits. The evacuees are following the same direction in the second graph. According to the results, the evacuees follow the correct directions. A special crowd behavior occurs in the members' area. Figure 19 shows the flow count of the west access of the members' area.

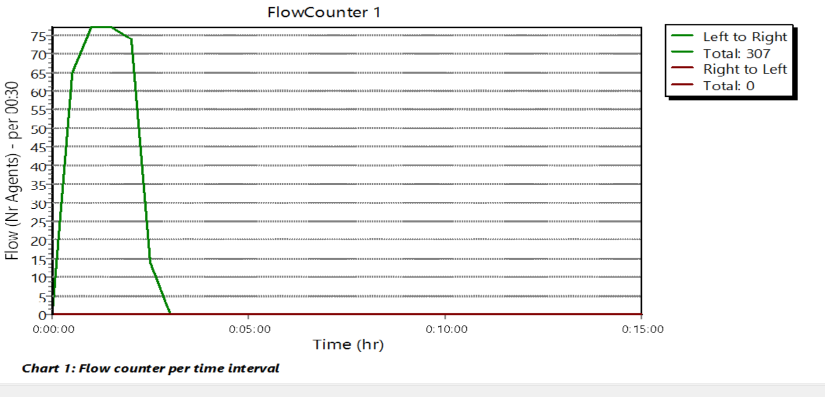


Figure 19: Flow Count of the West Access of the Members' Area

When an evacuation is triggered, the people from the members' area have to move upward to find the access route to the exit while the others are moving downward. The flow count describes the crowd dynamics of the members' area where people move upward first, then downward.

Overall, the TET (Total Evacuation Time) varies from 4:45 to 20:20 minutes depending on the numbers of evacuees and the conditions of the stadium. Over 50% of the crowd tends to evacuate during the first couple of minutes of the evacuation. According the simulation results, the crowd behaviors of the simulations are almost identical to those in real situations. The average density of the first two minutes of the evacuations is 2.2 people per square meter. The access stairs to the exits from the main bleachers are congested during the first few minutes of every evacuation scenario. When a random exit is blocked, the TET increases on an average of 40 seconds.

Pedestrian Dynamics (PD) software uses a different scheme but generates the same results as what SCP and Dijkstra algorithms do. The author changed the variable of the evacuating speed of crowd to improve the accuracy of the simulation. PD uses the triangular distribution for the speed variable of the algorithm (TRI (0.5, 1.75, 0.86)). The 0.5 meters per second is the average walking speed of people traveling on stairs. The speed of 1.75 meters per second is the average walking speed of a human being on ground. The speed of 0.86 meter per second is the average crowd moving speed (C, Browning, Baker, A.Herron, & Kram, 2006). In this research, normal distribution was used to get more accurate walking speed for the simulation: (NOML (1.15,0.2)). The author used μ as 1.15 and σ as 0.2.

According to the safety officials, the average TET of real evacuations is 20 minutes for the 7500 EVAC evacuation scenario. The standard deviation is 3minutes. According to the simulation results, for the same scenario the average TET is 23 minutes with the standard deviation as 2 minutes. The T- test results are listed below:

Mean1-Mean2=20.5-23=-2.5

SD=6.5955; SE=6.5955

90% Confidence

p= 0.35234

According to the T test results p (0.352) >0.1, therefore the difference is not significant at 10% confidence level. The simulation results do not reflect the real-world evacuations of Hancock Stadium. Mann-Whitney U test results are, Z score = -0.3676

P = 0.35569

U Value = 28

P < or = 0.1

According to the Man-Whitney U test the p is less than or equal to 0.1 (0.35567>0.1). It means the results are not significant at 10% confidence level. Therefore fail to reject the null hypothesis. The simulation results do not reflect the real-world evacuations of Hancock Stadium.

CHAPTER V

DISCUSSION

Current Simulation with Pedestrian Dynamic System

The development of the system of the Pedestrian Dynamic involves the drawing of the stadium, the moving behaviors, and path calculating. Figure 20 shows the process of the current system design. The beginning of the project is to identify the geometric physical data of the design of the stadium. The software automatically generates the access route and walking area during the compile process. The entry and exit have to be defined manually according to the physical design of the stadium. There is a special feature in Pedestrian Dynamics, which is to enable agent to identify where to show up and disappear. The next step is to change the parameters such as the number of evacuees, walking speed, and the distribution method of crowd according to the simulation scenarios. In the third step, the simulation is performed 10 times per scenario to make sure the accuracy of the results. Finally the system generates the reports to identify the crowd behaviors in the stadium, such as density area, time taken to evacuate, where the crowd bottleneck occurs, etc.

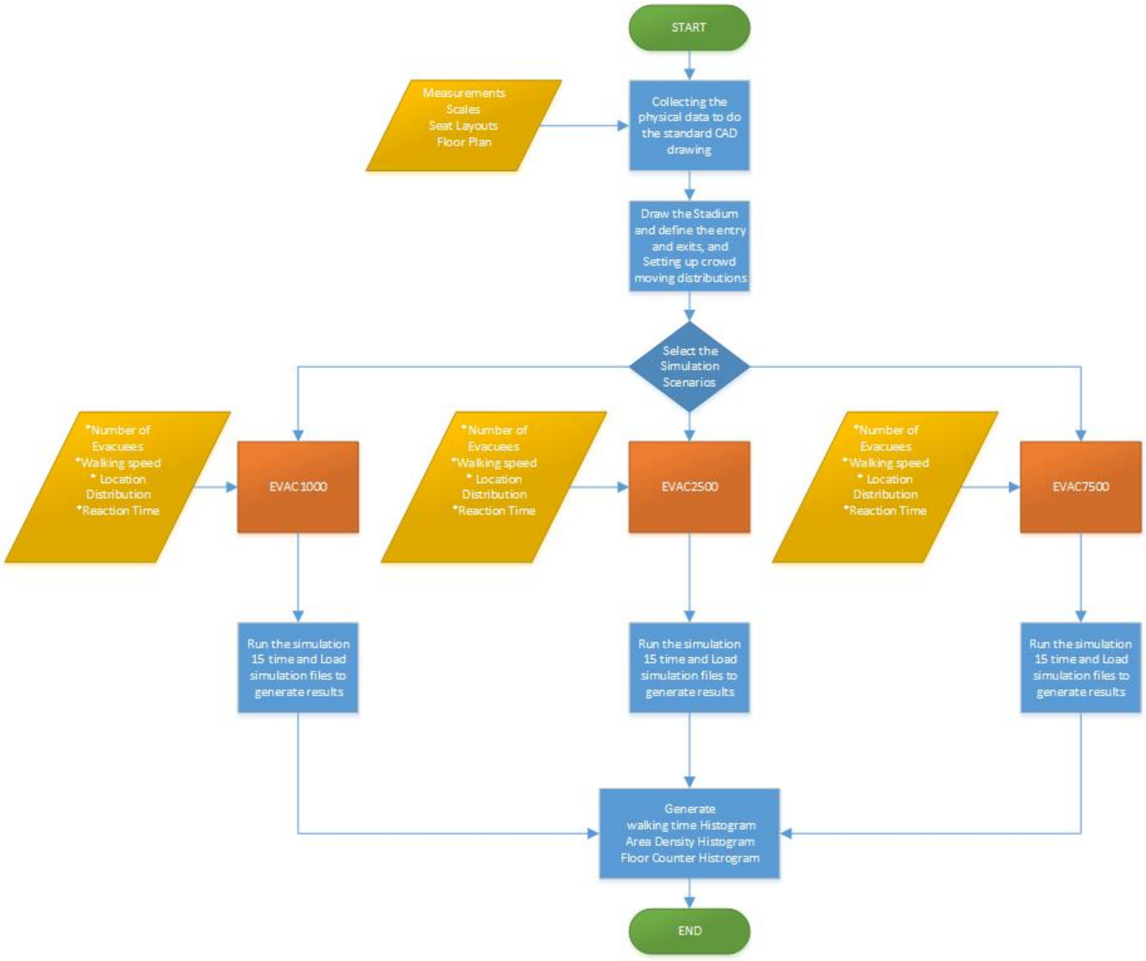


Figure 20: The Current Pedestrian Dynamics System

Researchers have implemented equations to calculate the path and the time for evacuation. The potential function used to compute the evacuation path of the crowd is shown in equation (1).

$$\alpha\int_p 1ds+ \beta\int_p 1dt+\gamma\int_p 1gdt \tag{1}$$

Where *ds* means that the integral is taken with respect to path length. *dt* means the integral is taken with respect to time. The letters of α,β,γ are constants for the equation. (Treuille, Seth , & Zoran , 2006). The first phase ($\alpha\int_p 1ds$) describes the path how path length effect to the evacuation. $\beta\int_p 1dt$ solves the time of an evacuation and $\gamma\int_p 1gdt$ means the discomfort level in an evacuation. The three factors stated above which are distance, time and discomfort level are considered to calculate the optimized path in an evacuation (Same as the calculation of the SCP).

A formula to calculate the evacuation time T_{tet} for fans to escape from the stadium is stated below.

$$T_{tet}= 1/(f_pB')*(N_a-N) + K_s/V \qquad (2)$$

Where the f_p is moving rate from an exit, B' is the width of the exit door, N_a is total number of evacuees. N is who can escape, which can be expressed in terms of the flow rate of people moving from the building (Candt & Chow, 2006). K_s is the distance to the location of first evacuee. V is the speed of the evacuee. Figure 21 shows the flow chart of how the formulas have been developed and used for the evacuation process.

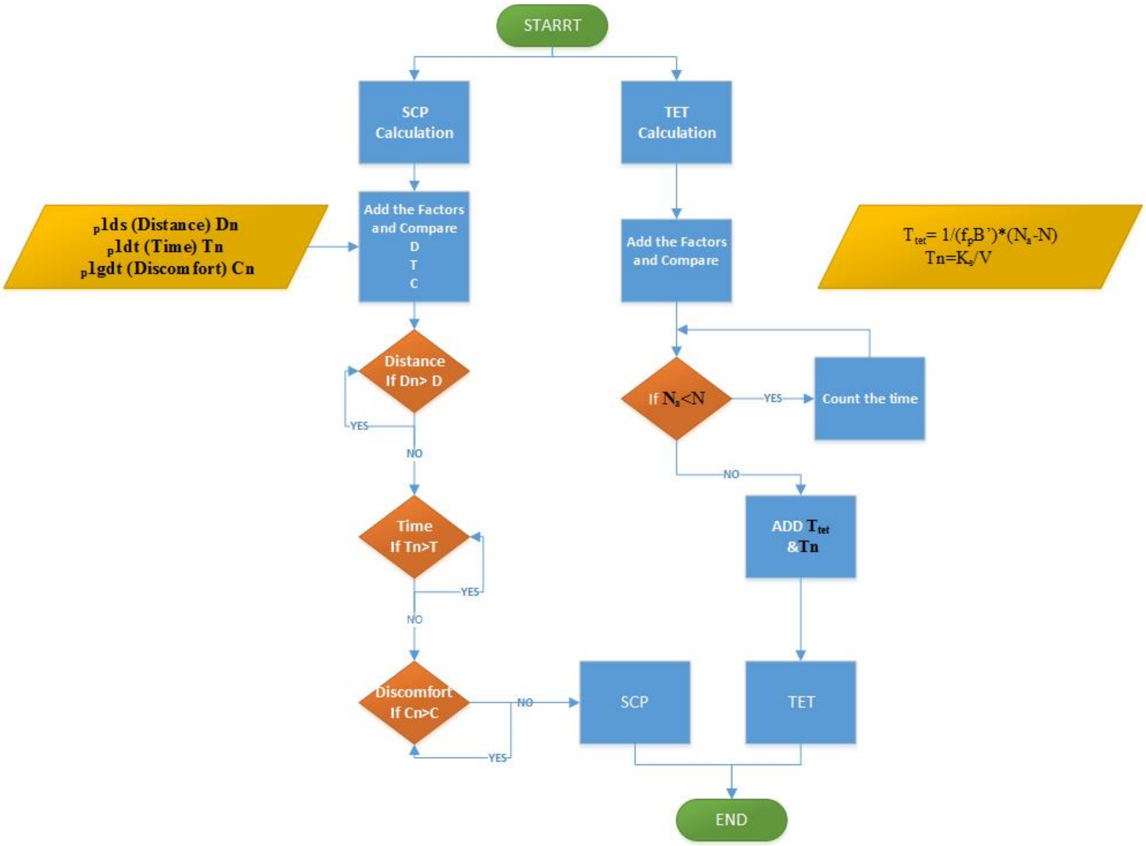
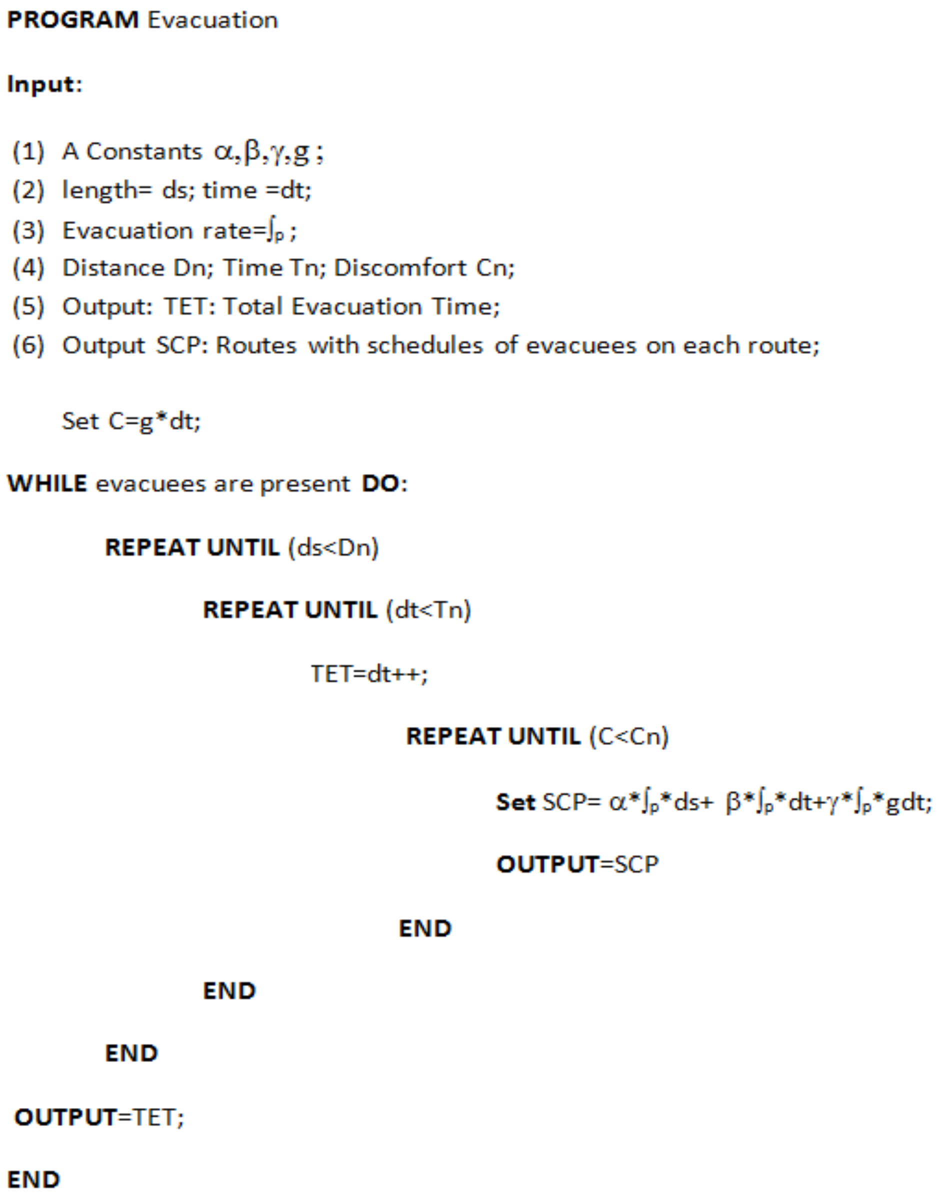


Figure 21: Process of Formulas Development

The combination of the two formulas provides the end results of Total Evacuation Time for the simulation. TET is used in the equations of the calculations of Shortest Cleared Path. Figure 22 shows the pseudo codes of the development of the formula.



```
PROGRAM Evacuation

Input:

(1) A Constants $\alpha,\beta,\gamma,g$ ;
(2) length= ds; time =dt;
(3) Evacuation rate=$\int_p$ ;
(4) Distance Dn; Time Tn; Discomfort Cn;
(5) Output: TET: Total Evacuation Time;
(6) Output SCP: Routes with schedules of evacuees on each route;

    Set C=g*dt;

WHILE evacuees are present DO:

    REPEAT UNTIL (ds<Dn)

        REPEAT UNTIL (dt<Tn)

            TET=dt++;

                REPEAT UNTIL (C<Cn)

                    Set SCP= $\alpha*\int_p*ds+ \beta*\int_p*dt+\gamma*\int_p*gdt$;

                    OUTPUT=SCP

                END

        END

    END

 OUTPUT=TET;

END
```

Figure 22: Pseudo Codes for Development of the Formula

In summary, the Pedestrian Dynamics uses its own algorithms and formulas to calculate the shortest cleared path and evacuation time. Most crowd evacuation algorithms depend on Dijkstra algorithm or with addition of some advanced methods such as discomfort level. Some distribution methods have been used to program the walking speed and the crowd behavior of the evacuation simulation. Triangular distribution and normal distribution have been using to calculating the walking speed of the stair and access routes. Empirical distribution has been used to program the crowd behavior of the evacuation simulation. The SCP calculation assists to calculate the TET by adding a count to the time factor of the algorithms which is more accurate than using the formula of $T_{tet}= 1/(f_pB')*(N_a-N) + K_s/V$.

Range of Validity

PD simulations can imitate reality like evacuation models for specific evacuation scenarios. However the simulation does not exhibit some of the risks, behaviors that we would fine in real emergency evacuation. Even simplified simulation models to study the complex behaviors of large number of people in different evacuation scenarios, will lack realistic or unexpected limitations. One of the major limitation is there is no proper way to profile an agent with social and psychological intelligence assessment capabilities. The simulation software is capable of performing almost real evacuation using advanced features such as collision detection, collision avoiding and intelligent movement dynamics.

In many stadiums, people with disabilities could also be in evacuation. Some facilities are capable of providing designated evacuation routes for people with disabilities. PD simulation software has no proper way to design evacuation methods for people with disabilities. In this research, the author assumed that the people with disabilities would follow the evacuation protocols and instructions the same as normal people do.

Many audiences are not aware of some evacuation procedures and where the emergency exits are. To generate a smooth evacuation for the stadium, people must be aware of the evacuation protocols and procedures. Otherwise crowd patterns will be changed, resulting in crowd bottlenecks and pile-ups. Therefore another assumption is that the whole crowd is fully aware of the evacuation protocols and procedure of the building.

Range of validity of the parameters may vary from one evacuation to another. Mostly validity of the parameters is moderate in same evacuation scenarios. SCP (shortest cleared path), TET (Total evacuation time), response time can be validated according to the situation.

Due to the lack of availability of concrete data regarding the crowd flow of the stadium, the author performed both Mann-Whitney U-test and one-tailed T-test to analyze the results. Both tests generated results, which indicated that the P value is not significant at 90% confidence level. Due to the varying dynamics such as alcohol and state of emotions, the agent cannot be programmed to include all the necessary variables, which in turn generates the 90% confidence level. Therefore, the author failed at rejecting the null hypothesis. The simulation results do not reflect the real-world evacuations of Hancock Stadium. The author believes that one of the reasons that the simulation results do not reflect the real-world evacuations is due to the fact that all the agents have not been programmed individually. Behaviors of individuals vary from one another. However if the option of feeding specific data per agent was available for the given software, different results could be expected from the Mann-Whitney U-test and One-tail T-test.

During this research, the author gained more knowledge about the essentiality and the time saving opportunities of the software utilized. It was a great challenge to develop algorithms, which reflects the actual human behavior, which could be fed into the software. During the conduction of this research the author detected the presence of numerous uncertainties of which it was difficult to determine the factors. However, the following data was collected, fluctuations in the speed of walking, emotional levels, levels of intoxication, visibility, the layout of the stadium and physical strength. In addition to these, it is possible that other factors would exist which would also need to be evaluated to develop a more accurate system.

CHAPTER VI

CONCLUSIONS

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 could generate 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.

The research 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 7,500 spectators occupy the stadium. The simulation results demonstrated that it took nearly 20 minutes to evacuate the whole crowd out of the building. Using the density histogram, the development of a crowd bottleneck in the area with congestion could be identified. 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 have enough space to evacuate the crowd from the building. But some places such as the access stairs to the benchers tend to be easily blocked during the full-scale evacuation. According to the one-tailed T test and Mann-Whitney U-test, the null hypothesis was rejected because it showed that the simulation results did not reflect the real evacuations in Hancock Stadium. The reason for the difference is that the virtual agents are not programmed with enough capabilities to reflect the moving dynamics. Also the agents have one defined moving speed during evacuations. It needs to be changed according to the characteristics of the location such as stairs, walking areas, elevated access routes, etc. Changes were made to simulate the real walking speed of the stadium. In the revised model, the walking parameters were defined based on the characteristics of the access routes. For example the upward walking speed on stair is $0.5ms^{-1}$. The upward walking speed of the elevated route is $1.2ms^{-1}$.After the adjustment; the simulation could reflect the real simulations better, which contributes to the effectiveness of the safety management plan.

CHAPTER VII

RECOMMENDATIONS AND FUTURE WORK

One recommendation for the safety management of Hancock Stadium is to have the real-time video data to evaluate the crowd behaviors and to compare the situations with the simulations. The simulations would be validated by using the video footages, which makes the simulation more realistic. Having video footages of the crowd also creates opportunities to detect the states of audiences' minds, such as angry, happy, and excitement, by analyzing the micro expression of the body. There is some software in the market with the capability of detecting micro expressions. Some software systems can detect the micro expressions of a human's face. For example, iMortion® is capable of gaining the emotional insight from the analysis of a person's facial expressions. It can detect the emotions such as joy, anger, feat, and sadness (Inc, 2015). The condition of the mental status of a human being may affect the time when the person makes a sudden decision. Another task of future research is to validate the walking speed and the agents with advanced feature, such as emotional related behavior. In this case, the speed of the individuals becomes a significant factor of the evacuation. The walking speed of a human being can be changed by many factors during an evacuation, i.e. characteristics of the walking path, visibility, crowd flow, etc.

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