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A crowd simulation for a large-scale indoor venue - a case study of Taipei Arena

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Abstract

Previous research into crowd evacuation simulation has focused on exploring general buildings and urban pedestrian traffic. Crowd evacuation simulation of large-scale venues has been limited. This study verifies the applicability of adopting Pathfinder 2011, agent-based simulation software, to develop a simulation model for crowd evacuation at a large-scale venue. Taipei Arena was chosen for the case study. Different evacuation simulation conditions and the results demonstrate that the steering movement mode of Pathfinder is suitable for simulating the movement of heterogeneous crowds and L-shaped movement in stairways and raised seating areas. Two functions of Pathfinder, "occupant grouping" and "designation of evacuation path" can construct an occupant movement model of a large-scaled indoor venue and each evacuation path to consist of one final destination (main entrance) and one mid-point (exits in the seating area or corridor platform). Such guidance is much more important for people seated in raised seating areas on higher floors within a large-scale indoor venue than for other areas in this venue, due to the limitations of stair width and inclination.

Introduction

Multi-purpose, large-scale indoor sporting/entertainment venues, such as those held at sports centers, concert halls, and auditoriums, will host performances, sports competitions, concerts, and other activities. Due to the large internal spaces at these venues, a vertical complex space structure, and numerous exits inside these venues, it can be difficult to find evacuation paths during emergencies. Therefore, congestion often occurs during crowd evacuation. In the case of disasters, such as fire, explosions, and structural collapse, people may easily push on each other due to panic, thus congesting the passages or exits further, resulting in serious injury or death.

For rapid and safe evacuation of crowds at a large-scale indoor venue, carefully planned crowd evacuation preplanning is necessary. To preplan such safe crowd evacuation and carry out an evacuation simulation on an actual scene with live crowds requires a lot of manpower and material. High-risk evacuation cannot be simulated. On the other hand, computing power has increased dramatically and research on behavioral characteristics of crowd movements is also matured. Today more and more countries in the world today have been conducting safety assessments of crowd evacuation using computer simulation software. Currently, there are only a few studies on crowd evacuation of a large-scale venue, and most studies have focused on crowd evacuation of general buildings.

Crowd movements inside the large-scale venue are significantly different than those in the general buildings. Crowd movement in the seated area will not over in the general buildings. The seats in a large-scale venue are mostly installed on the terraces to allow the viewers to see the activities clearly and are divided into a few seating areas. These seating areas are connected with the plane level by longitudinal stair-like walkways and then connected to the passage areas and exits. Thus, crowd movements in large-scale venues can be divided into four stages: Selection of exit, moving to the stair-style longitudinal walkway along the seats from the seating area, moving from the stair-style longitudinal walkway to the passage area, and heading to the exit along the passageway. Crowd movements at Stages II and III have the L-shaped evacuation characteristics of a large-scale venue.

Pathfinder is specific-purposed and agent-based simulation software for crowd evacuation. The model considers the microscopic and macroscopic perspectives, and integrates movement manipulation behaviors and real limitations to simulate the crowd behaviors (*Pathfinder Technical Reference Manual*, 2011). As the latest evacuation simulation software suggests, it provides a three-dimensional visualized graphic interface and visualized tools to allow users to perform crowd simulation. It uses a set of complete three-dimensional triangular grid design and parameter settings to empower occupants with certain decision-making capabilities. It allows each occupant to determine in real time the moving direction according to the location and walking speed so as to predict the path choice behavior. It can automatically compute each occupant's evacuation path and evacuation time and compute the evacuation time of people in a specific area and the occupant flow rate for specific exits.

As *Pathfinder* estimates evacuation time on the basis of individual movements, and it offers multiple simulation options, it has great potential for the application to a large-scale venue crowd evacuation simulation. As a result, the current study adopted the simulation software to explore how to use Pathfinder to process the interactive relationships between people, people and building structures, and the specific behavior model. The applicability of using Pathfinder to simulate crowd evacuation of a large-scale venue is discussed in this study.

Literature Review

Schadschneider *et al*. (2009) categorized microscopic models of crowd simulation in space discrete and space continuous models and presented the advantages and drawbacks of the different microscopic models. Schomborg *et al*., (2011) pointed out that macroscopic models of crowd simulation are less time consuming. For a Sports Arena, they can calculate the optimal assignment of the attendees to the available exits and provide the best distribution of evacuees on the exit routes. Manley (2012) further divided the simulation models of crowd evacuation into macro, meso, and micro model categories.

Studies on evacuation software application are still limited. Weckman *et al*. (1999) observed an evacuation drill in a theater scene of a fire without warning to learn about crowd evacuation behavior. Then they applied the software EVACNET+, Simulex, Building EXODUS and ASERI to analyze the theater evacuation preplanning plan for 600 people. The simulation results suggested that ASERI and EVACNET+ simulated total evacuation time had great differences, while the Simulex and Building EXODUS simulation results were very similar. An (2006) proposed using the manual computation and STEPS methods to analyze the evacuation safety of Beijing National Stadium, the National Aquatics Center, and Tianjin Olympic Center Stadium.

Jiang and Ma (2007) evaluated building fire prevention assessment software to choose a Building EXODUS suitable for a simulation analysis of large-scale buildings. They simulated the evacuation of a total of 64,408 people in case of a fire in a large-scale exhibition hall. Based on the different evacuation simulation conditions and the results, partitioned evacuation and personnel guidance produced better evacuation benefits, and the difference was more significant for people seated on higher floors, mainly because of the limitation of stair width. As people can be evacuated in different sections in different directions, that process can easily result in the congestion of crowd evacuation and the extension of the evacuation time. However, as there is no audience seating area, that study was different from the topic of this study. You (2010), for the Taipei Gymnasium (Taipei Arena predecessor), applied Simulex and Building EXODUS in a simulation evaluation of occupant evacuation in a large-scale indoor space. He found that Building EXODUS analysis was more conservative. However, the crowd evacuation process depicted by Building EXODUS was more optimistic than that by Simulex, that is, at the same point in the evacuation process, more people were evacuated when simulated by Building EXODUS than when simulated by Simulex.

The Case Study

Simulation Models of Pathfinder

The basic elements of crowd evacuation simulation include: Definition of the occupant behaviors during the evacuation, venue spatial environmental modeling, occupant decision-making modeling, and computer simulation experiments. The occupant decision-making model is a model that describes the individual behaviors of the evacuee and thus is the core of any crowd evacuation simulation. The pathfinder occupant movement model can be further divided into a steering model and a SFPE model. The steering model is based on inverse steering behaviors that control the movement of the occupant through path planning, steering mechanism and collision processing. Path searching is based on human behavior theories. If the distance between people and the nearest path is beyond a certain threshold value, the algorithm will automatically re-plan a new path to adjust occupant movement and avoid collision. The so-called inverse steering behaviors model is the process used to evaluate possible moving directions and selection of the path with minimum cost to a group of people. Possible moving directions are related to the current state and speed of the people involved. The cost of every possible moving direction is then evaluated based on four steering behavioral perspectives (search direction, maintaining of space, avoiding walls and avoiding personnel). The cost of moving in a certain direction can be obtained after weighing these factors. In addition, using the priority settings of Pathfinder, it was found that people of larger build and good physical condition will get priority by pushing. The SFPE model determines moving speed, occupant evacuation rate at the door and the occupant evacuation rate of passage by room occupant density, applying the evacuation flow model from the fire protection manual (Nelson & Mowrer, 2002) and occupant behaviors in a fire (Society of Fire Protection Engineers, 2003). The building can be divided into door, room and stairs, and the size of door will limit the flow rate of the occupants.

Compared to the flow-based SFPE model, the behavior-based steering model is more suitable for simulating the movement of heterogeneous crowds and a L-shaped movement in stairways and raised seating areas. The SFPE model can better simulate the real scene of crowd evacuation and the evacuation paths (Ye *et al*., 2011). The steering model also provides an access priority system to simulate interpersonal concessions. When the occupant detects the presence of people at different priority levels, the person with higher priority of access does not need to keep any distance from the person with lower priority of access to allow the occupant of higher priority access to push the person with lower priority of access as necessary. The occupant of lower priority of access does not search in the moving direction and keeps interpersonal space to allow the occupant of higher priority of access to pass. In addition, the model also includes a behavioral mechanism to address the conflicts from movement of the crowd evacuation to simulate the possible arched phenomenon and reverse movement when the occupants are going through a narrow passage or a door.

Numerical Spatial Model for the Taipei Arena

Taipei Arena is a steel reinforced concrete building with two underground floors and five ground floors. Its base area is 114,522 m^2 and total floor area is 88,401 m^2. The bowl-shaped seating area in the venue has a total of 14,960 fixed seats. The main exits include nine doors at the northern entrance region on the first floor and five doors on the south entrance on the second floor. This current study used the basic spatial blocks provided by Pathfinder, including floor, room, door, exit, stair, and ramp to construct a numerical building model for Taipei Arena main stadium, as shown in Figure 1.

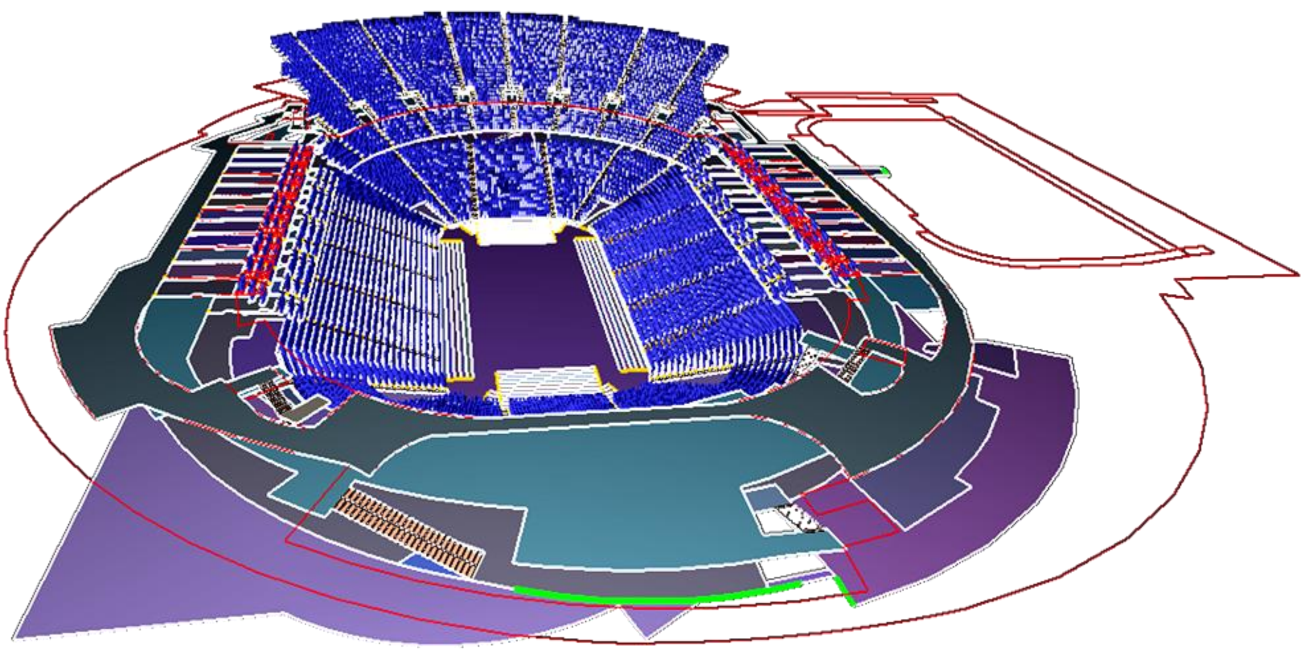


Fig. 1. Numerical Spatial Model of Taipei Arena

Parameter Setting

Pathfinder software considers the walking speed variations of all people. These walking speed settings include: Fixed value, values following uniform distribution, and values following normal distribution. Due to the variance in gender and age of participants at large scale activities, this study assumes that the walking speed of participants follows the normal distribution. According to the observation made by You (2010), the walking speed in the Taipei Arena varies from 0.46 m/s to 0.84 m/s. The average value of the walking speed is 0.65 m/s. The standard deviation for the walking speed is 0.095 m/s. The assumption is that the standard deviation of walking speed is fixed and the range is within 2 standard deviations (higher and lower) from the mean. We gradually magnified the average walking speed. Six experiments for the distribution parameters of walking speeds were designed for the study, as given in Table 1. On the other side, according to the human body measurement data for Taiwan, the average shoulder breadth of male laborers age 18 to 65 is about 45 cm and the average shoulder breadth of female laborers is about 41 cm (Wang & Wang, 1997). Therefore, human shoulder breadth was set at 43 cm.

In order to validate the rationality of the walking speed settings for this large-scale indoor venue, we compared the simulation results to the real evacuation data collected by You (2010). Only 2,089 people in the seating areas on the third floor to the fifth floor were evacuated. It took 13 minutes and 17 seconds for the last person to arrive at the main entrance on the first floor for evacuation according to real observations recorded by a video camera. Our experimental results for using the steering movement model and parameter setting for the crowd evacuation simulation are shown in Table 1. It was found that the evacuation time for the first parameter setting was almost equal to the result of the physical experiment for crowd evacuation. Therefore, we adopted the first parameter setting for walking speed in the next simulation model.

Table 1. Results of Simulation Model Verification

Parameter Experiment	*Walking Speed (m/s)*				*Evacuation Time*
	Mean	*Std. Dev.*	*Minimum*	*Maximum*	
1	0.650	0.095	0.460	0.840	13’19’’
2	0.715	0.095	0.525	0.905	12’20’’
3	0.780	0.095	0.590	0.970	10’37’’
4	0.845	0.095	0.655	1.035	9’58’’
5	0.910	0.095	0.720	1.100	9’01’’
6	0.975	0.095	0.785	1.165	8’26’’

Occupant Movement Setting

Pathfinder simulation software determines the path for the evacuation based on the shortest path algorithm. When it simulates the crowd evacuation of a large-scale indoor venue, we found the mid-point setting of the evacuation line to be very important, such that the occupant movement can thus comply with the characteristics of *L*-shaped movement inside the large-scale venue. In addition, horizontal movement along one- seat spacing by one- seat spacing should be prohibited. Two functions of Pathfinder, “occupant grouping” and “designation of evacuation path” were adopted to construct an occupant movement model for a large-scaled indoor venue. That is, occupants in different seating areas will have different crowd evacuation paths. Each evacuation path consists of one final destination (the main entrance) and one mid-point (exits in the seating area or corridor platform). Based on the building structure configuration of the Taipei Arena, we set six sub-models of occupant movements for the different seating areas, as shown in Figure 2.

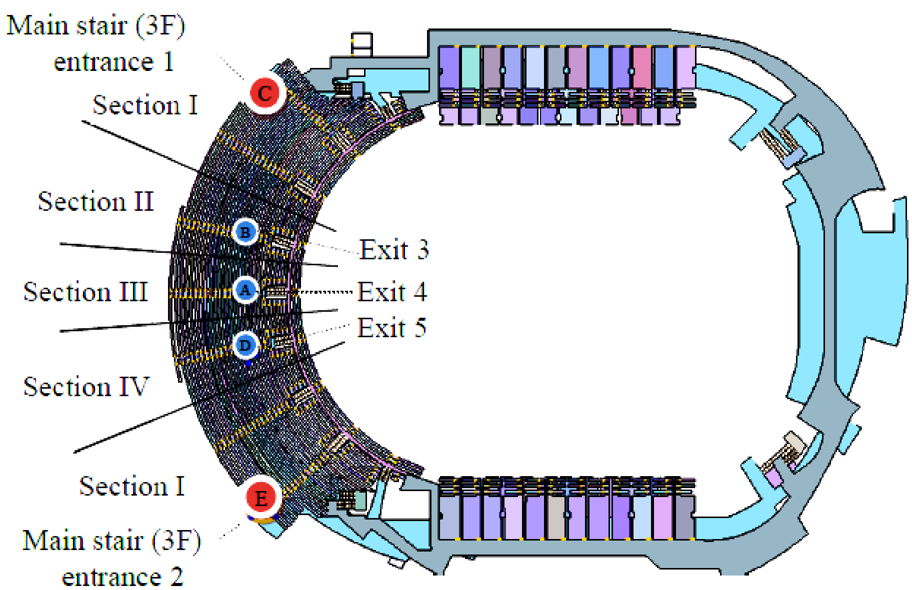
Evacuation Strategies and Simulation Results

Critical goals for enhancing the evacuation efficiency of crowd evacuation of a large-scale indoor venue are to increase the number of evacuation moving lines and decrease the conflict of evacuation moving lines. Effects of the closing/opening of existing emergency exits/staircases and the installing of new stair passages are discussed in this study. An alternative of a new stair passage was suggested as shown in Figure 3. Four scenarios were presented and evaluated to explore the evacuation efficiency of Taipei Arena. The summary of the simulation results are shown in Table 2.

According to the simulation results, in terms of evacuation time, the optimal evacuation strategy would be Scenario 4 with an evacuation time of 18 minutes 26 seconds. With Scenario 1 as the basis, by installing a new stair passage, the evacuation time can be considerably reduced by 4 minutes 55 seconds to improve evacuation efficiency by 18%. Its marginal effect would be greater than the improvement from opening all the existing emergency exits/staircases (6%). Moreover, the last person to arrive at the exit on the first floor is always seated in Sections II, III, and IV on the third to the fifth floors. Because they are relatively far away from the main entrance on the third floor of the main stairs, they need to be guided in the evacuation. A possible occupant movement conflict in aisle, stair or corridor corner can occur. Thus guidance is much more important in raised seating areas within an auditorium than in other areas of the same venue.

Table 2. Results of Simulation Model with Different Evacuation Strategies

Evacuation Strategy	*Evacuation Time*	*Marginal Effect*
Close emergency exits/staircases	24’06’’	-
Open emergency exits/staircases	22’41’’	Decrease 1’21’’
Close emergency exits/staircases & install a new stair passage	19’11’’	Decrease 4’55’’
Open emergency exits/staircases & install a new stair passage	18’26’’	Decrease 5’40’’



Submodel 1: People seated in the first underground floor plain seating area can move freely, and thus, they can leave the venue via the nearest exit to the main entrance.
Submodel 2: People in the ladder-style raised seating area from the first underground floor to the second floor on the ground can walk along the ladder-style longitudinal walkway to the corridor platform on the second floor before choosing any exit to go to the main entrance.
Submodel 3: People seated in the Section I of ladder-style raised seating area from the third to the fifth floors on the ground can walk along the ladder-style longitudinal walkway to get to the corridor platform on the third floor before choosing any exit to go to the main entrance.
Submodel 4: People in Section II of the ladder-style raised seating area from the third to the fifth floors enter the corridor of the third floor through Exit 3 and leave the third floor via the entrance platform on the third floor of the main stairs to go to the main entrance.
Submodel 5: People in Section IV of the ladder-style raised seating area from the third to the fifth floors enter the corridor on the third floor through Exit 5 and leave the third floor via the second platform on the third floor of the main stairs to go to the main entrance.
Submodel 6: People in Section III of the ladder-style raised seating area from the third to the fifth floors enter the corridor on the third floor through Exit 4 and leave the third floor via the first or the second platform on the third floor of the main stairs to go to the main entrance.

Fig. 2. Seating Sections from the Third to the Fifth Floors

According to the simulation results presented by You (2010), the total evacuation time for Scenario 1 is 14 minutes 18 seconds and 14 minutes 48 seconds when adopting the simulation software, Simulex and Building EXODUS, respectively. The evacuation time for the same number of evacuated people is longer using Pathfinder compared to that for Simulex and Building EXODUS. The Pathfinder 2011 simulator considers both microscopic and macroscopic perspectives of crowd simulation, and integrates movement manipulation behaviors and real limitations to simulate crowd behaviors. For a large-scale indoor venue, the mesoscopic simulator Pathfinder is more conservative than the macroscopic simulators, Simulex and Building EXODUS. The main difference is that the macroscopic models that describe people moving do not take into consideration actual interactions between people.

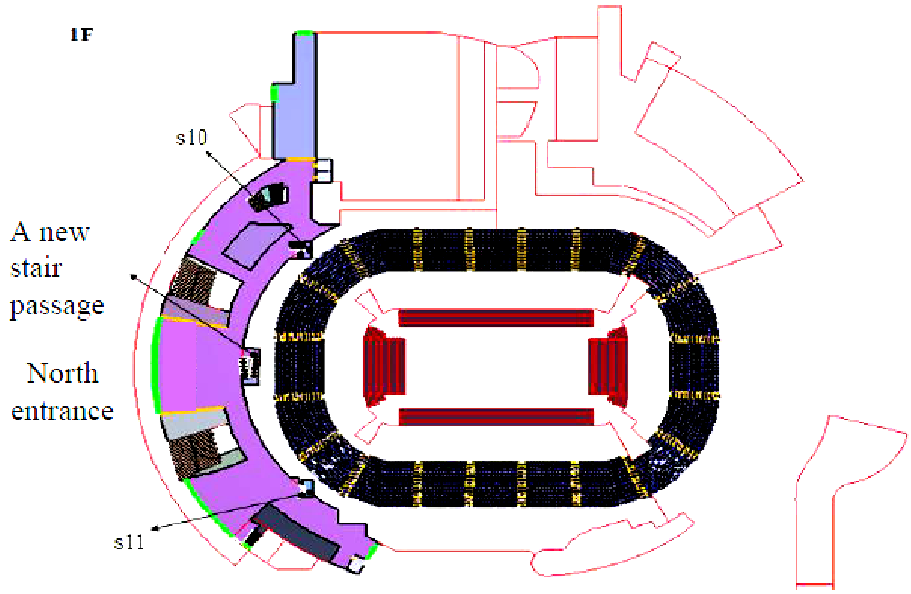


Fig. 3. A Layout of a New Stair Passage

Conclusion

This study applied the agent-based Pathfinder software to successfully represent both time and space changes in large-scale venue crowd evacuation using the steering model. In this study, we determined the special L-shaped movement characteristics of large-scale venue crowd evacuation can be captured by using the “personnel grouping” and “designation of evacuation path” functions of Pathfinder. Furthermore, people in different seating areas must be assigned different evacuation paths, so occupant movement conflict can be mitigated. Moreover, people have different walking speeds due to differences in gender and age, and thus this study conducted a simulation of heterogeneous crowd evacuation. Installing a new stair passage would be more helpful than opening all the existing emergency exits/staircases. The diverse effect of crowds in a large-scale venue is significant.

Future development of crowd evacuation models should include more detailed factors of crowd movement and focus on the impact of individual characteristics and crowd movement on evacuation time, for example, both physiological and psychological factors and the interactive relationships of the people. In terms of using Pathfinder in large-scale venue crowd evacuation simulation, by adding more path choice models (herd-following path choice and fixed path choice) and incorporating the proxemics theory and panic factors into the personnel movement model, Pathfinder can apparently improve the disadvantages of the crowd behavior model. Further, the types of probability distributions included in Pathfinder only include uniform and normal probability distributions and the probability distributions should be improved further to meet the needs of actual practical application.

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