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An agent-based simulation system for concert venue crowd evacuation modeling in the presence of a fire disaster

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ABSTRACT

A key activity in emergency management is planning and preparation for disaster. If the right safety measures are implemented beforehand, harmful effects can be significantly mitigated. However, evaluation and selection of effective measures is difficult due to the numerous scenarios that exist in most emergency environments coupled with the high associated cost of testing such scenarios. An agent-based system employs a computational model of autonomous interacting agents in an environment with the purpose of assessing the emergent behavior of the group. This paper presents a prototype of a computer simulation and decision support system that uses agent-based modeling to simulate crowd evacuation in the presence of a fire disaster and provides for testing of multiple disaster scenarios at virtually no cost. The prototype is unique in the current literature as it is specifically designed to simulate a concert venue setting such as a stadium or auditorium and is highly configurable allowing for user definition of concert venues with any arrangement of seats, pathways, stages, exits, and people as well as the definition of multiple fires with fire and smoke dynamics included.

1. Introduction

Of paramount importance to emergency managers is the question of how to prepare for as yet unseen disasters. Proper safety measures can literally mean the difference between life and death for large groups of affected people. However, emergency situations and their associated safety measures are highly specific to the environment in which they exist and there are generally numerous scenarios that must be considered. The cost of testing these multiple scenarios is oftentimes prohibitive (Jain & McLean, 2008). Thus, evaluation and selection of effective safety measures for emergency preparedness is quite difficult and is often left to the subjective judgment of an emergency manager.

Computer modeling and simulation seeks to remedy this problem by allowing for testing of multiple environment-specific scenarios at low cost. Agent-based systems use a computational model of autonomous agents that move and interact with each other and their environment. Such systems use a *bottom-up* modeling approach in which system control is decentralized and governed only by the behavior of the agents (Borshchev & Filippov, 2004). Agent-based modeling is the preferable technique for simulation of systems with a large number of active objects (e.g., people, business units, animals, etc.) that are dependent on the order/timing of events for the following reasons: (1) it allows for the capture of highly complex dynamics, (2) it can be implemented with little or no knowledge of the global interdependencies and/or aggregate effects of the system, and (3) it is easier to build upon as model changes generally require local not global adjustments (Borshchev & Filippov, 2004). The development of agent-based systems for emergency planning and preparedness remains an open research area as there exist a multitude of disaster environments that have yet to be addressed (Jain & McLean, 2008).

This paper presents a prototype of an Agent-based Decision Support System (ABS) for the simulation of crowd evacuation in the presence of a fire disaster for venues that are specifically intended for mass gatherings such as stadiums and auditoriums. The goal of the system is to allow for multiple scenario testing and decision support for the planning and preparedness phase of emergency management with regards to fire disasters at concert venues. The system is designed for emergency managers, police, and any administrators who are charged with fire disaster mitigation planning for concert venues. Users of the system can benefit by evaluating the effects of potential safety measures such as restrictions on the maximum number of people, wider pathways, additional exits, and fewer seats on crowd evacuation dynamics. The system is unique as it is specifically designed to simulate evacuation of a concert venue setting rather than an urban roadways or building evacuation setting as is prevalent in the literature. High

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densities of people and relatively limited exit routes and exit points are common characteristics of concert venues and their combination make such venues a significant concern for emergency managers. Additionally, the ABS system is highly configurable allowing for user definition of a concert venue with any number and arrangement of seats and bleachers, aisles and path ways, stages and playing fields, exits, and people and also allows for the definition of multiple fires with dynamics of fire spreading and smoke production included. The contribution of this study is twofold:

1. It provides an agent-based system that is specifically designed for crowd evacuation simulation of concert venues during a fire disaster.
2. The system is built for customization and provides to the user the ability to define the layout and structure of the concert venue to be simulated. This allows the user to replicate the venue of concern and provides decision support for the planning and preparedness phases of emergency management.

The rest of this paper is organized as follows: Section 2 provides a brief survey of the current research on agent-based systems for crowd evacuation modeling, Section 3 gives a description of the prototype ABS system, Section 4 details experiments conducted using the system to simulate disaster scenarios for simulated replicas of actual concert venues, and Section 5 discusses future work necessary to enhance and transition this prototype system into a viable commercial software system.

2. Review of current research

Recent advances in computational speed have made the construction of complex simulation systems more feasible. Several recent studies involving agent-based models for crowd evacuation simulation exist in the current literature. These studies generally fall into one of three categories: (1) crowd evacuation of buildings, (2) crowd evacuation for urban roadways, and (3) crowd behavior during evacuation.

Bonomi, Manzoni, Pisano, and Vizzari (2009), Braun, Bodmann, and Musse (2005), Camillen et al. (2009), Fangqin and Aizhu (2008), Filippoupolitis, Hey, Loukas, Gelenbe, and Timotheou (2008), Ha and Lykotrafitis (2012), He and Zhao (2010), Massaguer, Balasubramanian, Mehrotra, and Venkatasubramanian (2006), Okaya and Takahashi (2011), Pan, Han, Dauber, and Law (2006), Pelechano and Badler (2006), Shi, Ren, and Chen (2009), Tang and Ren (2008), Yamamoto (2013), Yang, Wang, and Liu (2011, 2012) apply agent-based modeling to simulate the evacuation of buildings. In Ha and Lykotrafitis (2012) an agent-based system is used to model panic effects during evacuation of a building. Filippoupolitis et al. (2008), Shi et al. (2009), Tang and Ren (2008), Yang et al. (2011) provide an agent-based model to simulate building evacuation during a fire disaster. Fangqin and Aizhu (2008) provides an agent-based simulation model for building evacuation during a fire disaster which uses computational fluid dynamics to model fire dynamics and spatial analysis of GIS data to model peoples' knowledge of the building structure. Okaya and Takahashi (2011) employs a Belief-Desire-Intention (BDI) model to model human relationships and investigate their effects on building evacuation dynamics. Pelechano and Badler (2006) developed a simulation model for building evacuation by crowds who might not know the structure's connectivity or who find routes accidentally blocked. Yamamoto (2013) provides an agent-based model to simulate building evacuations during earthquake and fire disasters. Yang et al. (2012) integrates multiple agent-based models at differing resolutions (i.e., macro resolution and micro resolution) to simulate building evacuation dynamics.

Anh, Daniel, Du, Drogoul, and An (2012), Handford and Rogers (2011), Lucas, Martinez, Sickinger, and Roginski (2007), Shendarkar, Vasudevan, Lee, and Son (2006), Balmer, Nagel, and Raney (2004) employ agent-based modeling to simulate crowd evacuation dynamics of urban roadways. Anh et al. (2012) provides a hybrid agent-based model for roadway evacuation simulation that combines macro and micro level simulations to increase overall simulation efficiency while capturing necessary low-level simulation details. In Lucas et al. (2007) and Shendarkar et al. (2006) emergency aspects of an urban roadway evacuation are modeled including fires, gunmen, and police personnel. In Handford and Rogers (2011) the interdependency of driver behaviors is modeled in the context of roadway evacuation.

Banerjee, Abukmail, and Kraemer (2009), Ben, Huang, Zhuang, Yan, and Xu (2013), Chu, Pan, and Law (2011), Heliövaara, Korhonen, Hostikka, and Ehtamo (2012), Laughery (2001), Lee, Son, and Jin (2010), Liang, Low, Lees, Cai, and Zhou (2010), Norling (2004), Pan, Han, Dauber, and Law (2007), Ren, Yang, and Jin (2009), Sharma and Lohgaonkar (2010), Tsai et al. (2011), Wang, Li, Liu, and Cui (2011), Yang, Ren, and Wu (2012) apply agent-based models to study crowd behavior during evacuation. Banerjee et al. (2009) employs a layered intelligence model to efficiently simulate agent-based crowd evacuation and demonstrate the model's scalability to larger numbers of agents. In Ben et al. (2013) the evacuation environment is modeled using a cellular automata model while an agent-based model governs the behavior of evacuees. The model is used to study evacuation dynamics in environments with and without obstacles. Chu et al. (2011) incorporates behavioral theories from social science concerning group affiliations, group influences, and intra-group roles to model crowd evacuation dynamics. Heliövaara et al. (2012) uses an agent-based model to study crowd behavior in counterflow situations, that is situations in which groups of agents have opposing directions of movement. Laughery (2001), Lee et al. (2010), Norling (2004) employ a BDI framework to model the decision-making process of individuals in crowd evacuation scenarios. Liang et al. (2010) investigates the use of embedding information into the evacuation environment in order to influence crowd behavior in an evacuation. Pan et al. (2007) uses a multi-agent model to simulate behavior during evacuation that exhibits competitive, queuing, and herding behaviors while Ren et al. (2009) uses an agent-based model to simulate evacuation during an explosion disaster. Sharma and Lohgaonkar (2010) provides an agent-based model that has a fuzzy logic component for simulating human behavior and decisioning in an evacuation. The model is used to capture both individual and group behaviors in an emergency evacuation scenario. Tsai et al. (2011) provides a multi-agent evacuation simulation tool called ESCAPES that is specific to the airport domain and incorporates varying agent types, emotional interactions, informational interactions, and behavioral interactions. Wang et al. (2011) employs an ant colony evacuation model that includes avoidance and preferential path selection behaviors. Yang et al. (2012) proposes a multi-resolution agent-based model to simulate pedestrian flow in an evacuation.

A few studies have focused on specialized applications of agent-based crowd evacuation models. Carroll, Owen, and Hussein (2012) applies an agent-based model to simulate evacuation from a foot bridge. Song et al. (2013) employs an agent-based model to simulate evacuation from a train station under a bioterrorism attack. Wei, Xiong, Zhang, and Chen (2011) uses a grid simulation framework to address simulation efficiency for large agent-based evacuation models. Chen, Wang, and Liu (2011) provides a study that incorporates GIS data into a multi-agent system to simulate non-emergency evacuation of a sports stadium.

Of all the recent studies described above, the model of Chen et al. (2011) is the one that is most comparable to the model presented in this paper as it is focused on crowd evacuation of a concert venue (in this case a sports stadium). However, there are two main differences between the two models: (1) the model of this paper is designed to simulate any concert venue and allows for user definition of the layout and structure of the concert venue to be modeled while the model of Chen et al. (2011) is specific to a particular concert venue and does not allow for user customization and (2) the proposed model is designed to simulate emergency evacuation in the presence of a fire disaster and includes fire and smoke dynamics while the model of Chen et al. (2011) simulates a non-emergency evacuation.

As detailed in the previous section, the ABS system presented in this paper provides a unique contribution as it is specifically built for crowd evacuation of concert venues under a fire disaster and it allows for extensive user customization of the concert venue to be simulated. The prototype system is intended to be a decision support tool for the planning and preparedness phases of emergency management and seeks to mitigate the impact of fire disasters by allowing managers to simulate multiple scenarios and evaluate the effectiveness of potential safety measures to be implemented before a disaster occurrence. The following section describes the ABS system.

3. ABS simulation system

The prototype ABS system is designed to model a concert venue that includes seats, aisle and path ways, stages/playing fields, exits, and people. It allows for the specification of multiple fire with dynamics of fire spreading and smoke production included. The goal of the system is to simulate crowd evacuation for concert venue settings such as found in stadiums, auditoriums, or concert halls. The system uses an agent-based modeling approach in which individual autonomous agents interact with each other and their environment. In this application agents are people who are located in seats, path ways, and stages and are trying to quickly move to an exit while avoiding one or more fires. Fires are also represented as agents which are created and which spread and produce smoke. The system is intended for use in the planning and preparedness phases of emergency management and offers the following benefits to emergency managers and other administrators charged with fire disaster mitigation planning for a concert venue.

1. The ability to specify customized environments with any number and arrangement of seats, path ways, stages/playing fields, exits, and people. This allows managers to more accurately replicate the stadia/auditoriums that are of interest to them.
2. The ability to specify multiple fires each with user-specified fire spread and smoke production rates.
3. The ability to simulate multiple scenarios and safety measures (e.g., wider path ways, additional exits, etc.) at virtually no cost and with relatively fast result turnaround. This allows managers to test a large number of possibilities and makes for better evaluation of the various safety measures. Ultimately, this leads to planning decisions that are data-driven rather than subjective.

The ABS system is implemented using a combination of NetLogo (an agent-based modeling and simulation development environment) and Java programming languages. The following sections describe the three major components of the system: environment setup, fire dynamics, and person movement.

3.1. Environment setup

For managers and planners, the ability to construct simulation environments that are relevant to their concerns is critical. The use of generic simulations may be helpful for general training purposes but in the end planners wish to accurately replicate the environment that they are obligated to protect. The ABS system is designed to be highly customizable and allows for the specification of any setup of seats or bleachers, aisle and path ways, stages or playing fields, exits, and people.

In a concert venue setting there is a large concentration of people in a small enclosed area and many of them will be viewing the event from the seating area. Seats are specified in groups or blocks made up of rows and columns (i.e., number of seats per row). The user specifies the number of rows and number of seats per row as well as the direction for the seats to face and the location (x–y coordinate) for placement of the block of seats. Additionally, the aisle width and separation between seats in a row can be specified by the user. In order to maintain the correct separation and aisle width for blocks of seats facing potentially at any angle, the system internally represents seats using the polar coordinate system and converts these to Cartesian coordinates for placement in the x–y plane.

Concert venues can have varying structures and differing setups for path ways between seating areas, stages, and exits. To allow for the configuration of a wide range of possible path ways, the system represents path ways as polygons each defined by a set of vertices. The user specifies the x–y coordinates of the vertices for each polygonal path way via an input file. The system then "draws" these path ways on the environment. To correctly paint the inside of polygonal path ways, the ray-casting geometrical algorithm is used to determine if a point is inside a polygon or not. The algorithm uses a horizontal ray emanating from the point to be tested and calculates the number of intersections with line segments that make up the polygon.[1] An advantage of the ray-casting algorithm is its fast computation time. However, a drawback of the algorithm is that it may give inconsistent results for points that lie directly on an edge of the polygon.

In order to overcome this drawback, the following heuristic is used. First, the ray-casting algorithm is used to paint all points on the interior of a polygon. Then, the edges of the polygon are colored by a temporary painting agent that traverses the vertices of the polygon, painting as it travels. After all polygons are drawn on the environment, this painting agent is discarded.

Stages and/or playing fields can also occur in a variety of shapes and configurations, and thus the system represents these as polygonal structures as well. The user specifies these in the same way as for path ways, via a set of vertices. The system paints pathways and stages in (differing) colors that can also be set by the user. Users can specify an exit via an x–y coordinate location and an outgoing direction. Exits can be placed at the boundary of simulation environment or at any inner location if desired. Large exit ways can be specified as a sequence of several exits side by side.

The system allows for the placement of people in seating areas, in path ways, and on stages/playing fields. The number of people to be placed in each of these areas is controlled by the user. This allows managers to test several event scenarios including scenarios in which people are entering or leaving the venue before or after the event as well as scenarios in which most of the people are seated during the event.

Fig. 1 gives an example simulation environment (without people) constructed by the system. In the figure the path ways are colored gray, the stage is yellow, and the seats are brown. There are two exits colored yellow in the east and west directions. There are six blocks of seats: two blocks of seats are placed to the left of the simulation environment and are facing east, two blocks

[1] For more information on the ray-casting geometric algorithm, please see Sutherland, Sproull, and Schumaker (1974).

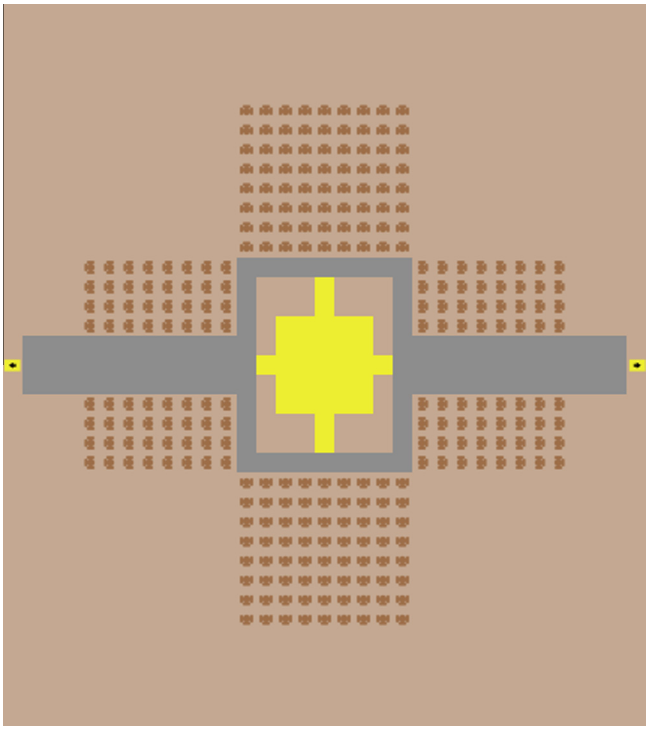

Fig. 1. Example simulation environment without people.

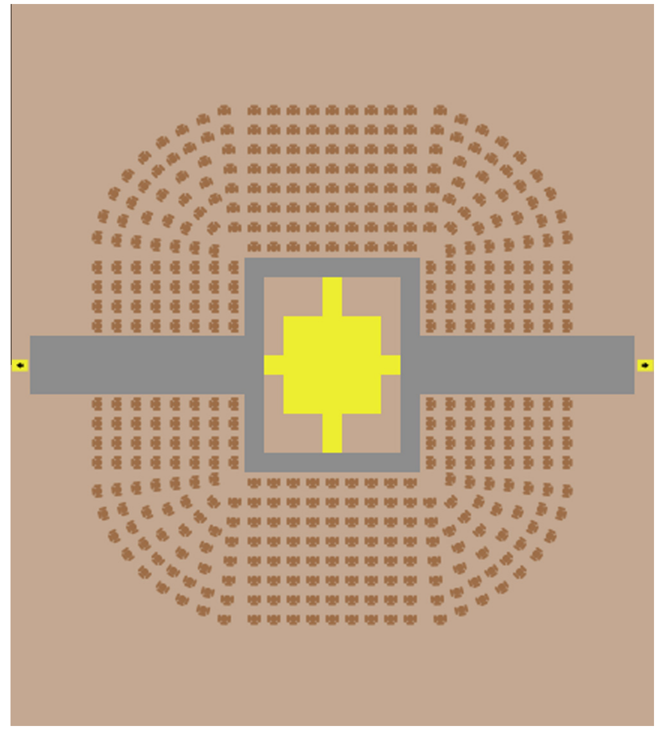

Fig. 2. Example simulation environment with curved rows of seats.

are placed to the right and facing west, one block is placed in the upper half of the environment and is facing south, and one block is placed in the lower half and is facing north.

Often a concert hall or auditorium may have not only rectangular blocks of seats in which the rows are straight (such as seen in Fig. 1) but also blocks of seats with curved rows. The system allows for the specification of blocks of seats with curved rows via an input file. For example, Fig. 2 shows the same environment as shown in Fig. 1 with an additional 4 "curved blocks" of seats in the northeast, southeast, southwest, and northwest corners of the environment.

The system uses an algorithm based on quadratic Bézier curves to plot blocks of seats with curved rows. Quadratic Bézier curves require a start and end point for the curve and a control point which governs the curvature produced. The user specifies the start, end, and control points for the backmost row of seats to be made. The user also specifies the number of rows to be drawn and the point that the seats in the rows should face. The system then draws the backmost row of seats using the quadratic Bézier curve equation given in Eq. (1). In the equation P_0 and P_2 are the start and end points of the curve, P_1 is the control point and t is a curve tracing parameter that varies between 0 and 1 ($t = 0$ defines the start point, $t = 1$ defines the end point).

$$B(t) = (1-t)^2 P_0 + 2(1-t)tP_1 + t^2 P_2, \quad t \in [0,1] \tag{1}$$

After drawing the backmost row of seats, the system then calculates new start, end, and control points for the 2nd backmost row which will have fewer seats and be closer to the specified facing point. A new start point is calculated by making a ray from the start point toward the facing point and calculating the x–y coordinate on the ray that is the correct aisle width distance away from the start point. The new end point and control point are made in a similar way. The system then uses these new points and Eq. (1) to draw the 2nd backmost curved row of seats. This procedure is then repeated until all rows have plotted. It should be noted that the curve tracing parameter t in Eq. (1) does not directly correlate to a distance between points on the curve and that varying t in regular intervals does not guarantee that points (and, thus seats) are placed with equivalent spacing in-between each pair of seats (Farin, 1997). In order to ensure seats are spaced evenly throughout a curved row, the following algorithm is used.

1. The curve tracing parameter t is initialized to 0 and a seat is placed at the start point of the curve.
2. A new point on the curve is generated using Eq. (1) by increasing parameter t by a small increment and then the distance of this point to the last placed seat is calculated.
3. If this distance is equivalent to the desired amount of spacing, a seat is placed at this point. If not, step 2 is repeated until a point that is the correct distance from the last placed seat is found. A new seat is then placed at this point.
4. New seats are placed using steps 2 and 3 above until the last seat placed has reached the end point of the row.

3.2. Fire dynamics

As mentioned above a user can specify multiple fires with associated rates of fire spreading and smoke production. Fires, like people, are represented as agents in the system. A fire will spread in a random direction at the specified rate and will produce smoke at the specified production rate. In the simulation environment agents representing people can be hurt either by being burned by fire or from accumulated smoke. The user specifies the minimum distance that a person must be from a fire before getting burned. The user also specifies the total amount of smoke that people in the simulation environment can tolerate before suffering from asphyxiation. As the fire(s) spread and produce smoke, the system records the amount of accumulated smoke and the number of people hurt by getting burned. Once the amount of smoke in the environment reaches the user-specified threshold, all remaining people in the environment (i.e., those who have not yet exited) are recorded as hurt.

3.3. Person movement

The purpose of the system is to simulate the evacuation of people in a concert venue environment under fire disaster conditions. People in the environment have one goal: to quickly move to an exit while avoiding fire. The algorithm governing person movement consists of three components: selection of an exit, movement from the seating area to a path way, and movement along a path way toward the selected exit. These three components are all influenced by a fourth component governing fire avoidance. At the start of the simulation, fire(s) are created and people in the seating area or in a path way select an exit. Each person selects the exit nearest to him/herself that is not blocked by fire. A person considers an exit to be blocked by fire if a fire is within a (user-specified) minimum distance from the exit or if the fire is directly between the person and the exit.

Once an exit has been selected, people in a seating area must move from their seat down an aisle toward a path way. A person in a front or side row seat may move directly onto a path way if that direction represents the shortest way toward his/her desired exit. A person not in a front or side row seat must move to an adjacent seat in the same row in the direction that represents the shortest way toward his/her desired exit. The system determines the type of seat a person is currently located at (i.e., front row, side row, or neither) by making a short distance scan of the area around the current seat in search of other seats directly in front or to the side. In order to determine which direction down an aisle a person should go to move toward his/her desired exit, the system calculates the distance from the exit to each of the adjacent seats (left and right) and selects the seat that is closer to the exit. People move from seat to seat down an aisle in this way until they reach a front or side row seat, and then can move directly onto a path way.

People on a path way must move toward their desired exit while staying on the path. As discussed in Section 3.1, the system paints path ways on the simulation environment. The environment is made up of many square shaped "patches" some of which are colored to represent a path way. Each path patch stores four directions representing north, south, east, and west. During environment setup, the system calculates allowed directions for each path patch by making a short distance scan from the center of the patch in each of these four directions in search of other patches that are not colored as a path way. If a scan from a path patch in a particular direction yields a non-path patch, then that direction is disallowed for the path patch in question. For example, if a patch is located in the middle of a wide path way, then the scans in each direction will not yield any non-path patches as this patch is surrounded by path patches. Thus, this patch will have four valid directions meaning that a person on this patch may move north, south, east, or west without moving off the path. If a patch is located on the edge of a path way, then the scan in one (or more) of the four directions will yield a non-path patch. This patch will then remove that direction from its list of valid directions meaning that a person on this patch will be disallowed from moving in that direction.

Thus, a person is moved along a path by selecting a valid direction from the patch that he/she is currently located at and moving some (user-specified) maximum distance. A person chooses from the available valid directions by calculating the absolute angular difference between each valid direction and the direction directly facing the desired exit. The valid patch direction with the minimum angular difference is then selected. Fig. 3 depicts an example direction selection of a person on a path patch. In the figure, a person must select one direction from three valid patch directions: north, east, and south, respectively (for this example suppose that the west direction is not valid for this patch). θ_1 in the figure represents the angle between the north patch heading and the heading directly facing the desired exit. θ_2 and θ_3 represent similar angles for the east and south patch headings, respectively. For this case, θ_2 has the minimum value and, thus the east patch direction is selected by the person agent.

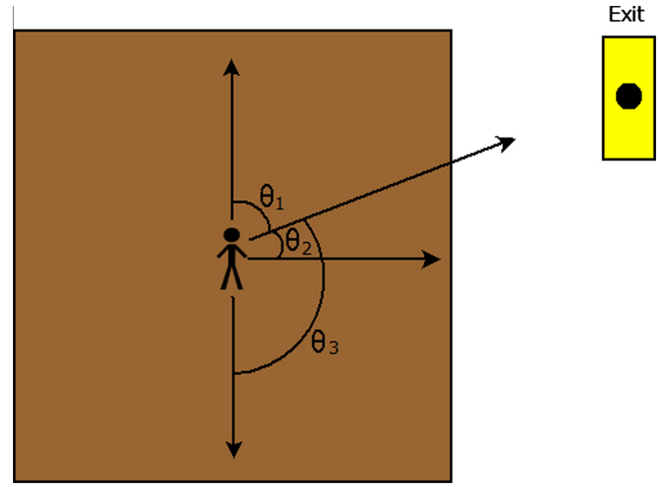

Fig. 3. Person Movement.

Although people on a path way may only move in one of four directions, fine-grained movement can be achieved by decreasing the size of the patches (and thereby increasing the total number of patches in the environment). In the system patch size is a parameter that is specified by the user. Fine-grained movement can also be achieved by increasing the number of possible valid patch directions, for example, by adding northeast, southeast, southwest, and northwest directions. Although the current prototype only includes four possible patch directions, the system can easily be extend to include more directions. Both of the above mentioned methods will increase the computational burden of the system as increasing the number of patches means that the system must process more objects and increasing the number of possible patch directions means the system must execute more computations per patch. Stages are represented in the same way as path ways and, thus, movement of people on stages is handled in the same way as described above.

As fires spread during a simulation run, exits that were originally unblocked by fire may become blocked. At each simulation step a person in the seating area or on a path way rechecks his/her desired exit and, if it is blocked, chooses a different exit in the same way as described above. Additionally as a person moves along a path way or down an aisle, fire may spread to block the path or aisle. At each simulation step a person makes a medium-range scan of the area in the direction he/she is heading in search of fires blocking the way. If any exist, the person recalculates his/her direction by removing the current direction from consideration and selecting a new direction in the same way as previously described. In this way a person attempts to avoid fire while moving toward an unblocked exit in a changing environment.

Fig. 4 displays a replica created by the system of a real auditorium at a mid-sized university. The figure contains people and fires and represents the state of the simulation world at a single point of time during a simulation run. In the figure there are two sets of exits (colored yellow), one to the south and one to the east with four blocks of curved row seats facing a small yellow colored stage (podium). In the figure pathways are colored gray and a fire is present at the south exits.

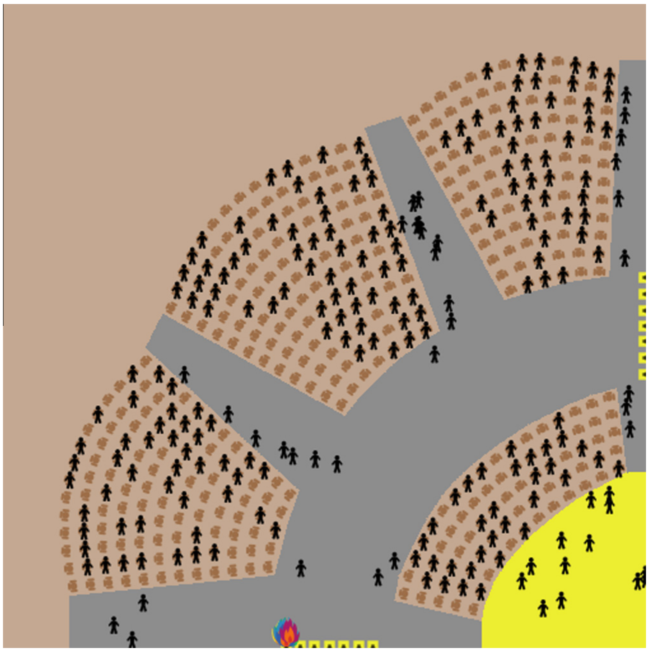

Fig. 4. Auditorium environment.

3.4. Replication of multi-level concert venues

Concert venues containing multiple levels such as raised or tiered seating areas or raised stages can also be replicated by the ABS system. This is accomplished through the specification of "blank" areas within the environment, that is areas that are neither seat, path, nor stage. These areas are prohibited for people to move onto and serve as boundaries demarking a raised area that a person cannot cross.

An example simulation environment depicting a multi-level concert venue created by the ABS system is given in Fig. 5. The simulation environment is a replica of a real sports stadium at a mid-sized university. In the figure the playing field is colored green, path ways are colored tan, and the black dots represent people most of whom are seated. There are four raised seating areas to the north, south, east, and west demarked by white outlines in the figure. The white outlines represent boundaries that people cannot move through. The seating areas to the south, east, and west are raised on the back and sides only meaning that people may move through the front of the seating area only. The north seating area is raised on all sides meaning that these bleachers are raised above playing field level and people in them must use exits within the area enclosed by white outlines rather than exits that are outside of the area. The figure depicts the start of a simulation run, before fire(s) are created.

4. Experiments

The ABS system described above is a proof-of-concept simulation and decision support system for concert venue environments in the presence of a fire disaster. As discussed in Section 2, the system is unique in the literature as to our knowledge no other study provides a general and customizable agent-based model for crowd evacuation simulation of concert venues. Thus, the intent of this section is to provide examples of how the system can be used by a manager or planner to simulate a fire disaster scenario and evaluate its impact in a real-world concert venue setting.

In the planning and preparedness phases of emergency management, a manager seeks to evaluate several disaster scenarios at a venue. Ideally, a manager wishes to gain insight as to how safe a particular environment is and what effects altering the environment (e.g., adding more exits, reducing seating capacity) would have. For this study, experiments are conducted for two concert venue environments: (1) an auditorium (given in Fig. 4) and (2) a sports stadium (given in Fig. 5). These environments are replicas of actual venues that exist at a mid-sized university. Additionally, four versions of each environment are constructed that vary the number of exits and the number of seating rows in the environment. After each venue environment is specified (as described in Section 3), a manager must specify the location, spread rate, and smoke production rate of the fire(s) to be simulated, the maximum amount of smoke that can be accumulated in the environment before everyone still in the environment succumbs to smoke inhalation, and the number of people in seating areas, on path ways, and on stages. Once these are specified, a simulation run may be executed.

Table 1 gives specifications of a subset of the experimental parameters used by the auditorium and stadium environments, respectively. The specifications in this table are kept constant over the four experimental versions for each environment.

In the table the *spread rate* parameter represents how fast the fire spreads in meters per second. Similarly, the *smoke rate* parameter represents the smoke accumulation rate as specified by smoke coloring per second and is based on the Ringelmann Scale (Kudlich, 1955) with color values ranging from 0 to 5 where 5 is maximum smoke (black color). The *max. smoke units* parameter specifies the limit for accumulated smoke in the environment and also uses the Ringelmann Scale.

Table 2 gives parameter settings for parameters that are varied over the four versions of the auditorium and stadium environments, respectively.

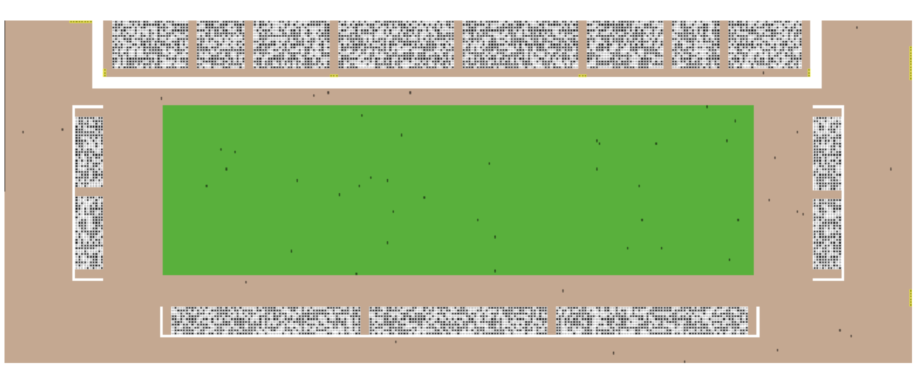

Fig. 5. Stadium environment with raised seating areas.

Table 1
Parameter settings for auditorium and stadium experiments (not varied over experimental versions).

Parameter	Stadium	Auditorium
No. people in seats	4000	365
No. people on paths	22	22
No. people on stages/ playing fields	33	33
Fire 1 spread rate	0.1 m/s	4.0 m/s
Fire 2 spread rate	0.2 m/s	n/a
Fire 3 spread rate	0.3 m/s	n/a
Fire smoke rate	0.0 units/s	0.00005 units/s
Fire location	Near north central of the raised seating area.	Near South Exit
Max. smoke units	n/a	5

Table 2
Parameter settings for auditorium and stadium environments (varied over experimental versions).

Exp#	Stadium environment		Auditorium environment	
	Seating capacity reduced by	No. of exits increased by	Seating capacity reduced by	No. of exits increased by
Exp#1	n/a	n/a	n/a	n/a
Exp#2	n/a	5	n/a	2
Exp#3	578	n/a	39	n/a
Exp#4	578	3	39	2

As can be seen from Table 2, Exp#1 refers to a simulation corresponding to the actual auditorium/stadium environment as it currently exists without any alteration. Exp#2 refers to a simulation of the auditorium/stadium environment with added exits. For the auditorium environment, two exits are added at the back of the seating area. For the stadium environment, 5 exits are added at the back of the raised seating area. Exp#3 refers to a simulation of the two environments with reduced seating capacity. For the auditorium environment, the front two rows from each of the rear seating blocks are removed which accounts for reduction of 39 seats. For the stadium environment, two whole seating blocks are removed from the raised seating area which resulted in reduction of 578 seats. Exp#4 refers to a simulation of the two environments with both added exits (as in Exp#2) and reduced seating capacity (as in Exp#3). Note that for the stadium environment, this combination resulted in adding 3 exits at the back of the raised seating area and removal of two whole seating blocks as discussed above. Removal of two whole seating blocks resulted in removal of two aisles and two exits at the end of these aisles respectively. Hence only 3 exits are added instead of 5 exits as used in Exp#2 above.

For the auditorium environment, the area is enclosed and smoke production is a significant concern; thus a smoke rate and maximum accumulated smoke limit are specified as shown in Table 1. For the stadium environment, the area is open and smoke production is not a significant concern as smoke can escape into the air; thus smoke rate is specified as 0.0 and no smoke limit is used. Suitable values for all parameters were calibrated for each environment during a number of preliminary experiments.

There are some aspects of the system that are simulated with random control and, thus individual simulation runs with the same environment and parameter specifications may vary. The simulation aspects that are controlled in this way include the placement of people in the various areas and the dynamics of fire spreading. For example, if the specification for number of people in the seating area of a particular environment is X, two simulation runs with

Table 3
Results for auditorium and stadium experiments.

Exp#	Stadium Env.			Auditorium Env.		
	Avg. % Hurt	Avg. Sim. Time (s)	Avg. $E(t_e)$	Avg. % Hurt	Avg. Sim. Time (s)	Avg. $E(t_e)$
Exp#1	6.70	1016.40	290.84	48.66	50.80	40.61
Exp#2	5.80	981.00	256.69	20.57	50.80	27.38
Exp#3	8.44	1001.30	318.44	48.22	50.90	40.94
Exp#4	7.14	1036.90	292.81	20.18	51.30	27.32

this specification will both have the same total number of people in the seating area but may differ as to which seats are actually filled by people and which seats are empty. The dynamics of fire spreading is governed in the same way; that is two simulation runs with the same specifications for fire location and spread rate may differ as to where the fire actually spreads over time.

Because of this potential variance between simulation runs (and between actual real-life circumstances), it is advisable for a manager to execute several simulation runs for a particular environment/scenario and note the average result.

Thus, a set of 10 simulation runs were executed for each of the four experiments for the auditorium and stadium environments, respectively with the specifications for fire and people as given by Table 1.[2] Table 3 gives the results of auditorium and stadium experiments. Displayed in the table are the average percentage of people hurt, the average simulation run time, and the average expected time for a person to exit from the stadium or auditorium environment, respectively for each of the four experiments. The simulation run time for an experiment represents the time at which the environment (stadium or auditorium) becomes completely uninhabitable, that is all the people remaining in the environment are hurt.

In Table 3, the expected time to exit is calculated by the following formula:

$$E(t_e) = \frac{\left(\sum_{i=1}^{n_e} t_{e_i}\right) + t_s n_h}{n_e + n_h} \tag{2}$$

where $E(t_e)$ is the expected time to exit in seconds, n_e is the total number of people that escaped, t_{e_i} is the time to exit for person i, t_s is the total simulation time, n_h is the total number of people hurt in the simulation (i.e., who did not escape).[3]

As can be seen in Table 3, adding more exits to either environment (Exp#2) reduces evacuees' expected exit time and results in a smaller percentage of people injured. In the case of the auditorium environment, this safety improvement is quite significant as the average percentage of people injured is reduced by 53.73%. However reducing seating capacity (Exp#3), perhaps counter-intuitively, does not have the same safety impact for either of the environments with only a slight improvement for the auditorium environment and a negative safety impact for the stadium environment. This is explained by the fact that reduced seating capacity can increase congestion at the venue by causing a higher percentage of seats to be filled. This increased congestion is evident in our experiments as the total number of people in the environment is kept constant while the number of seats in localized areas of the environment is reduced.

It is reasonable to ask the question, "why set up an experiment with reduced seating capacity without also reducing the total number of people in the environment?" The answer to this lies in what is and is not under the control of a venue manager. While

[2] All experiments are performed using Dell Precision T3500 workstation with Inter® Xeon® 2.8 Ghz processor and 3 GB of RAM with Windows 7 Professional 32-bit operating system.

[3] For a detailed discussion of expected value calculations, please see Loève (1977).

it is perfectly logical to expect that reducing the number of people at an event will increase safety, a venue manager cannot control how many people *actually attend* the event other than to limit the maximum number of people that may attend. For example, if a venue would normally be 50% filled for a particular event without reducing seating capacity, then with reduced seating capacity the same venue might now be 70% or 80% filled for the same event. For these experiments we wish to account for what is under the control of the venue manager and what is not, and thus, seating capacity is reduced (because this is under a manager's control) but the number of people attending the event is not reduced (because this is not under a manager's control).

As mentioned above, Exp#4 in Table 3 represents a scenario where both added exits and reduced seating capacity are employed. For the stadium environment, this combination does not improve the safety relative to the original scenario given by Exp#1, while for the auditorium environment this combination does improve the safety relative to the original scenario of Exp#1. These results indicate that congestion has a greater impact on the stadium environment than on the auditorium environment for the scenarios tested and prescribe adding exits to both the stadium and auditorium environments but do not recommend reducing seating capacity for the stadium environment.

The above experiments demonstrate how a manager can use the ABS system to evaluate many different scenarios/safety measures for real-world concert venues before zeroing in on actionable decisions to improve venue safety.

5. Future work and translation to commercial software system

This paper presents a prototype simulation and decision support system for crowd evacuation modeling of concert venues in the presence of a fire disaster. The purpose of the system is to allow for multiple scenario testing and evaluation of safety measures that seek to mitigate the effect of fire disasters with quick result turnaround and virtually no cost. The system employs an agent-based computational model to simulate the interaction of multiple autonomous agents with each other and their environment. Agent-based modeling is the preferable technique for simulation of multiple object systems because it can capture highly complex dynamics that are commonly seen in real-world applications (Borshchev & Filippov, 2004).

The system is meant for use during the planning and preparedness phases of emergency management and is highly customizable allowing users to specify simulation environments that accurately replicate concert venues that are of concern to them. The system is unique in the current literature as it focuses on a concert venue environment rather than urban roadway or building/floor evacuation setting. Concert venues are of significant interest to managers and planners as they have a high concentration of people in a relatively small area, and thus the selection of appropriate safety measures is a critical concern.

The ABS system described in this paper is a proof-of-concept system. As with any proof-of-concept prototype, there are a number of improvements that can be made to the system and there are several issues that must be addressed in order to translate the system into a viable commercial system.

The system could be improved by incorporating a more complex model of a person's decision making process into each person agent. A prevalent model from the literature that may be used is the BDI model which breaks down agent behavior into beliefs (information it has about the environment), desires (the state of affairs it wishes to create), and intentions (desires that it has committed to achieve) (Shendarkar et al., 2006). With such a model additional characteristics of human behavior in a disaster evacuation scenario could be captured such as erratic action and panic. Another improvement that could be made is in the area of fire dynamics. More accurate physical models of fire could include weather-related factors such as temperature, humidity, air pressure, and wind as well as topographical and fuel-related factors. Relevant topographical factors include the size, shape, and contour of the environment while fuel factors include the type of materials present in the environment (e.g., wooden or metallic seats).

As detailed in Section 3.4, the ABS system can model multi-level concert venues such as stadiums with raised or tiered seating or raised stages. Currently, the system is limited with respect to modeling multi-level venues in that people cannot move between levels. Thus, adding this modeling capability is another relevant improvement that can be made and would allow for the simulation of more complex concert venue environments.

In order to translate the prototype system into a viable commercial system, there are several issues that must be addressed. First off, the system is developed in part using the NetLogo programming language and development environment which specifies a license that restricts models built using it to non-commercial enterprises. [4] Thus, a commercial system would need to reverse-engineer many of the agent-based modeling specific functions of the NetLogo language such as graphical representation, agent movement and vision, and agent/environment reporting. Additionally, although the current system does allow for the specification of highly customized environments, this is accomplished via an input file which requires a minimum level of technical knowledge to create. An intuitive graphical user interface should be built for environment specification that makes this activity more user-friendly.

The ABS system described in this paper gives a proof-of-concept for simulation of concert venue crowd evacuation in the presence of a fire disaster. The potential benefits of translating this prototype into a viable commercial system are significant as such a system allows managers to execute multiple scenario testing and provides for data-driven decision support.

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[4] For more information on NetLogo license information, please refer to Wilensky (2012).

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