VALIDATION OF EVACUATION MODELS BASED ON VIDEO FOOTAGE OF PEOPLE LEAVING A ROOM

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ABSTRACT

More often engineers use evacuation models to assess and optimize safe escape possibilities, especially in buildings with grandstands. Point of attention by using these models is the reliability of the results and the scope of application. This article presents a comparison between three evacuation models (Simulex, BuildingEXODUS and Pathfinder) and basic flow capacity calculations.

The simulation models and flow calculations are validated by comparing the results with video footage of people leaving a room with grandstands in a normal situation (no evacuation). Three cases are presented; a lecture hall, a sports facility and a theater. The main differences between a non-emergency situation and a real evacuation are appointed.. Taking into account these differences, an analysis is made to determine if the results of the basic calculations are in line with the recorded phenomena. The same question is answered for the simulation models.

Besides analyzing the evacuation time of each room, the movement patterns and route selection of occupants around each bottleneck on the escape route are analyzed and replicated in the models. The input of the models is optimized based on this analysis.

This research results in an overview of the accuracy of each model and considers the necessary effort to use the model. The advantages and disadvantages of each model are listed and recommendations are given for obtaining the input values that lead to the most realistic results.

RESEARCH

Goal of this research is to assess the performance of different evacuation models when used for spaces with grandstands and relatively high occupant density. To achieve this, video recordings have been made of three cases in which people leave a space after an event. The cases are reproduced by basis flow calculations and simulation software. The total evacuation time as well as small scale behavior around obstacles is compared to the recordings to assess the models.

To clarify the terms in this paper, the parts of a grandstand are defined according to figure 1.

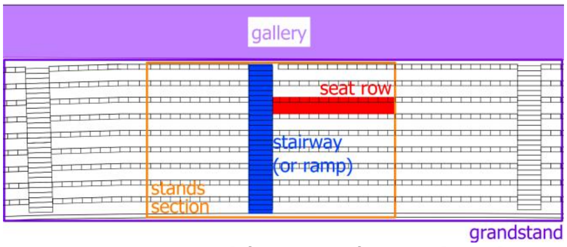

Figure 1: Terms used for parts of a grandstand

The three cases are described in table 1. All cases concern an everyday use situation, no fire alarm has been triggered.

Figure 2 shows a picture of the situation, just before the start of the egress. A schematic lay-out of each case is presented in figure 3.

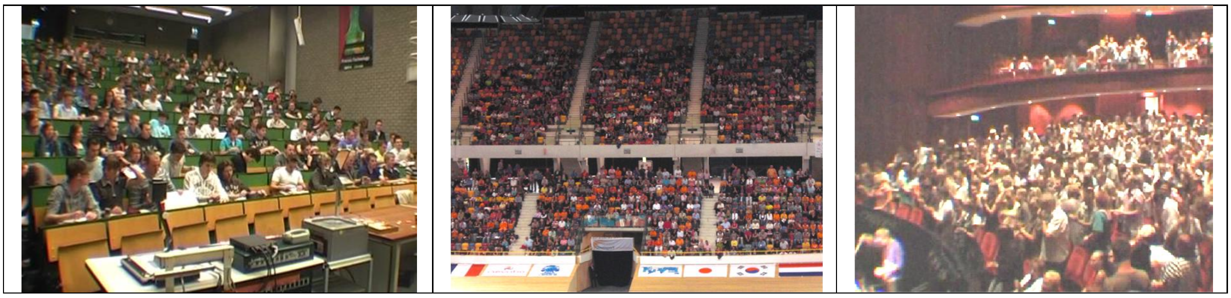

Figure 2: recorded cases: lecture hall, sports arena and theater

Table 1: Description of examined cases

Case	Lecture hall university	Sports arena	Theater
Number of events recorded	3	1	2
Event after which the egress is recorded	Lecture	International volleyball match	Musical
Occupation	160 / 104 / 65	2015	694 / 640
Percentage of maximum capacity	72 / 47 / 29 %	55 %	65 / 60 %
Nr of cameras (focused on stands)	6 (6)	7 (4)	6 (3)
Evacuation times measured of	Lecture hall	Grandstands	Theater hall
Used routes to leave grandstand similar to emergency situation	Yes	Yes	Yes
Use emergency doors and emergency staircases in the rest of the building (excluding the grandstands)	n/a	Partly	No
Well-defined starting point of egress	Yes	No [1)]	Yes
Lights	On	On	On
Tracking of people using the same route as they came in	No / yes / yes	No	No
Recordings announced	Yes [2)]	No	No
Possibility to pass taken seats	No	Possible, but difficult	Possible, but difficult
Presence of disabled people	No	Yes (1%)	Yes (1%)
Guidance by trained personnel	No	No	No
Doors opened by	Students	Occupants if not already opened	Personnel

1) There is still some activity on the court after the match, people leave gradually

2) People were informed about the presence of cameras and asked to leave the room as usual (first collecting their belongings etc), though directly after the lecture had ended.

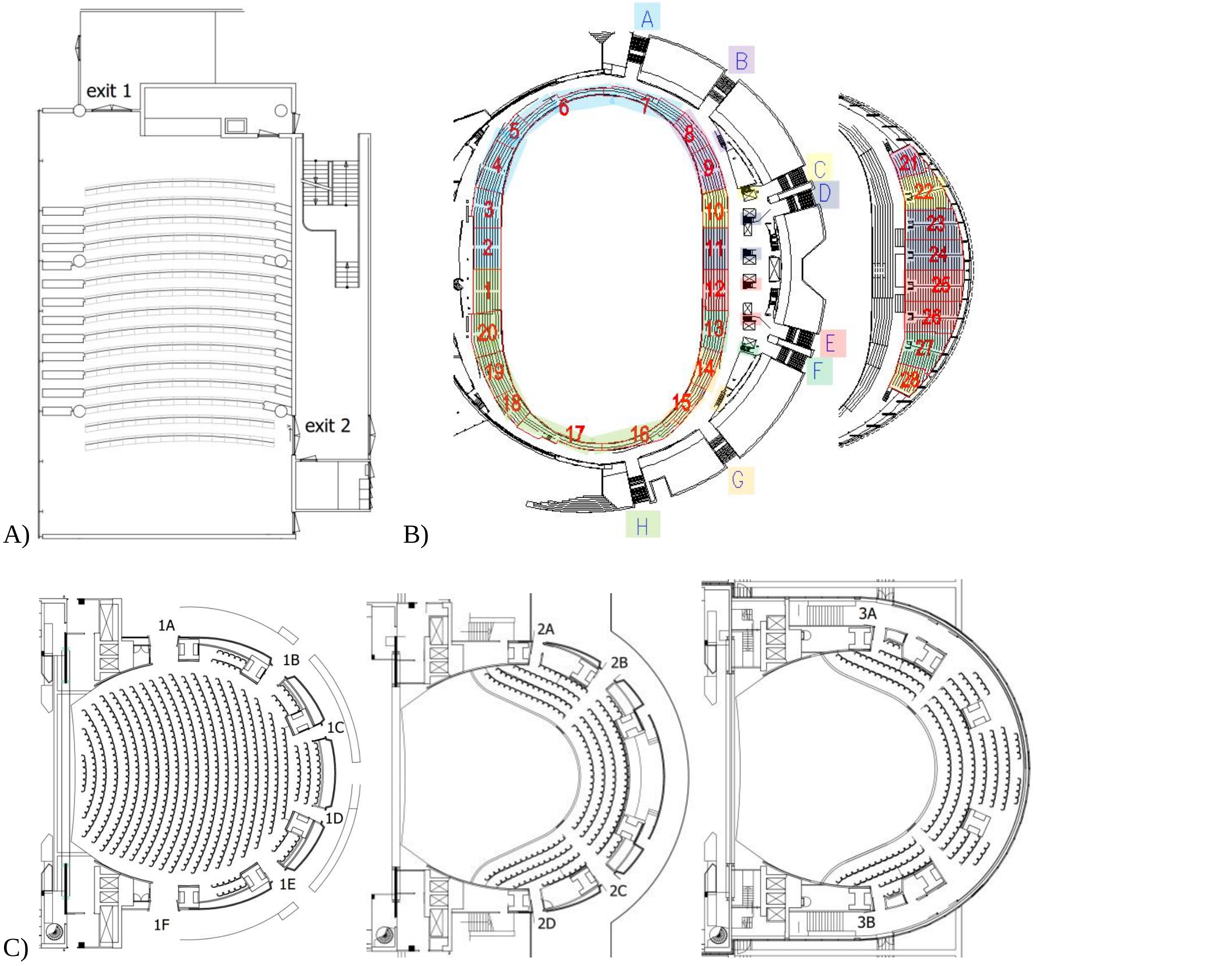

Figure 3: Schematic lay-out of examined cases. Lecture hall (A), sports arena (B), theater and two balconies (C).

Based on the recordings the following times are established:

Time to leave space	Pre-movement time (s)	Evacuation time (s)
Lecture hall (lecture 1)	0-35	94
Lecture hall (lecture 2)	0-35	52
Lecture hall (lecture 3)	19-98	114
Sports arena upper stands	0-145	254 [1)]
Sports arena lower stands	0-145	229 [1)]
Theater hall (musical 1)	0-30	121
Theater hall (musical 2)	0-45	124

1) Time until the stands are empty, people are physically still in the same space, on a gallery surrounding the stands.

MANUAL CALCULATIONS

Most simple way of predicting the evacuation time of spaces with grandstands is to model them as a sequence of obstacles, starting with the seat row and ending with the exit of the building or the examined part of the building. The total evacuation time is determined by the highest value for Td, see figure 4.

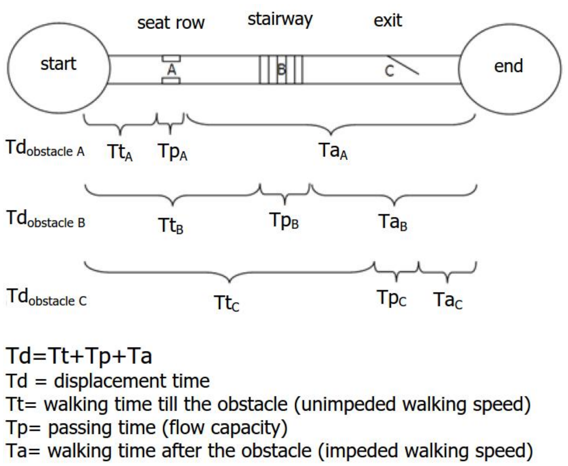

Figure 4: Simple calculation method

Many versions of these kind of movement models are available, varying in values for flow capacity and walking speed. The values used in this research originate from Dutch requirements and guidelines (such as the Dutch Building Decree 2012):

- Unimpeded walking speed horizontal: 1,60 m/s
- Unimpeded walking speed on stairs: 0,8 m/s
- Flow capacity horizontal corridor/door: 1,50 person/(m.s)
- Flow capacity stairs: 0,75 person/(m.s)
- Impeded walking speed horizontal: 0,37 m/s
- Impeded walking speed stairs: 0,32 m/s

Individual characteristics or behavior is not a factor in these models. Evacuation times depend on the number of people, the flow capacity of obstacles, and the distribution of people across the available routes (as given by the user).

To visualize the individual movement of occupants, more sophisticated models are available. Within the scope of this paper, Simulex, BuildingEXODUS and Pathfinder are reviewed.

EVACUATION MODELS

Simulex

Simulex [Thompson et al.] is a partial-behavior model that originates at the university of Edinburgh and is developed in the 90's. It uses individual agents that find the nearest exit by walking on a so called distance map, that holds the distance to the nearest exit for every point in space. A minimal mutual distance between agents and a certain distance from the physical boundaries avoid conflicts. The user can adjust the individual characteristics (walking speed and pre-movement time for example) and designate individuals or groups to certain exits.

BuildingExodus

BuildingExodus [Galea et al.] is developed by the University of Greenwich since 2004. Similar to Simulex it uses individual agents to simulate occupant movement. The building lay-out is transformed by the user to a grid of different kinds of nodes. Several behavior options enable the user to influence movement behavior and the way occupants interact with each other.

Pathfinder

Pathfinder [Thunderhead Engineering] is an agent based egress and human movement simulator. This program is developed by Thunderhead Engineering (USA). It uses steering behavior to model occupant motion. The movement environment is a 3D triangulated mesh designed to match the real dimensions of a building model. Occupants move from one virtual area to another, they can only move in places where a navigation mesh has been created. Every occupant gets his own behavioral characteristics, that defines goals for the occupant. Pathfinder supports two movement simulation modes. In "Steering" mode, occupants use the steering system to maintain a reasonable separation distance. In SFPE mode, occupants make no attempt to avoid each other and are allowed to interpenetrate, but doors impose a flow limit and velocity is controlled by density. In our research only Steering mode is included.

CASES

Comparison case 1: lecture hall

Figure 5 shows the results of the simulations in Simulex, BuildingExodus, Pathfinder and the manual calculation. The measured results during the real-life events are included as well.

The results from Simulex and BuildingExodus show fairly good comparison to the measured times. Small differences between simulex and exodus are caused by the way of modeling the stairway (flat floor vs stairs) and a column in front of exit 2 that impedes the flow in Simulex. Also in Pathfinder the flow stagnates around the columns in the lecture hall. Many conflicts occur when streams have to merge. In addition, in Pathfinder people often change between exits if the exits are close to each other. This causes more conflicts as the persons move around in opposite directions, mainly in narrow passages. This results in bigger deviations from the measured times. The manual simple calculation method also results in bigger deviations from the measured times. This is caused mainly by the fact that the average pre-movement time is added to the total time to pass the biggest obstacle. In reality there is a bigger variety in individual pre-movement times, leading to a different course of egress. In the simulation models each agent gets a own (random) pre-movement time, laying in a range between the starting times of the first and last person during the recordings. Also, the used values for flow capacity are more conservative than what is reached in the simulations.

Comparison case 2: sports arena

For the lower part of the stands there is quite a difference between the egress time that results from buildingexodus and the measured time. This is probably caused by the relatively low flow capacity on stairs in buildingexodus. The flow capacity on stairways in Exodus is explained later in this paper (see section 'stairway'). In two parts of the stands (9 and 14) the stairs are slightly skewed, which turns out to be in favor of the flow capacity. Therefore these times are less conservative compared to parts 10 – 13.
The higher part of the stands is sloped significantly, leading to lower flow capacity in reality. Therefore the buildingexodus simulation shows better agreement here, compared to the lower stands.

The simple movement models show an even bigger overprediction of the evacuation times. As in case 1, this is due to conservative values for flow capacity and the way pre-movement times are handled. In general the recorded pre-movement times show big variation in this case, because parts of the crowd stayed longer to watch the activity on the court after the match. This makes it harder to compare the case with simulations, without specifying individual pre-movement times. The other models show fairly good comparison to the measured times.

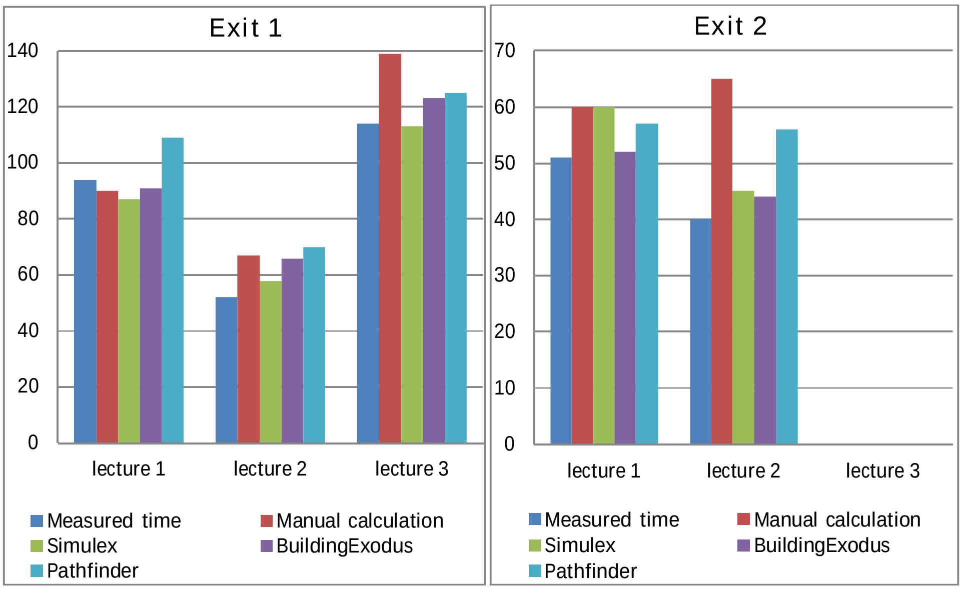

Figure 5: Results case 1 – times in lecture hall at exit 1 and exit 2 (in seconds)

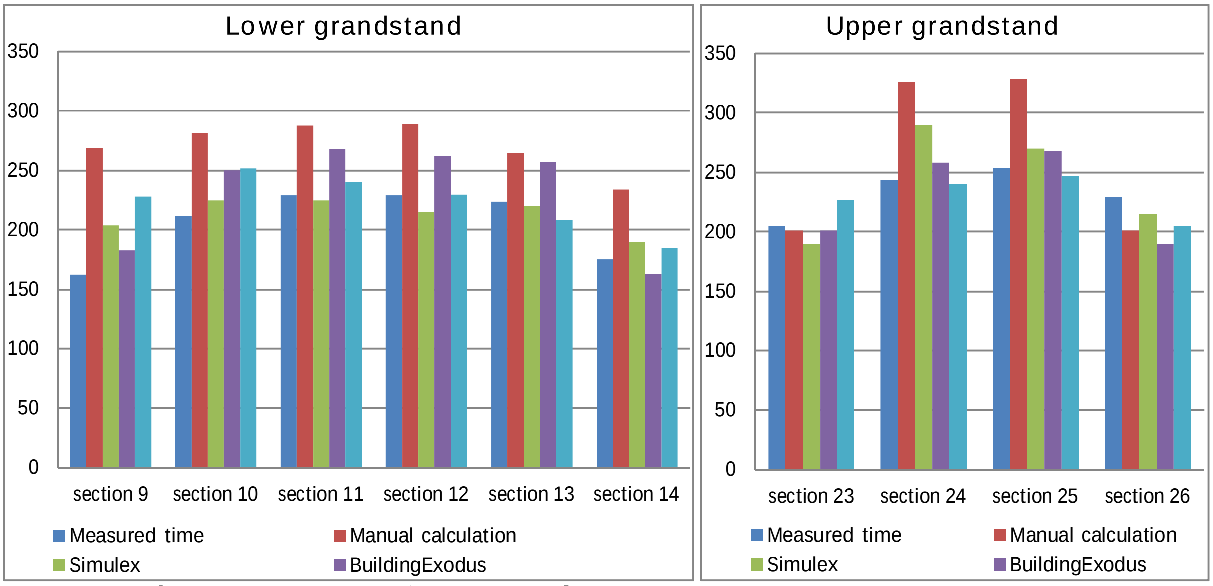

Figure 6: Results case 2 - sport arena (times in seconds)

Comparison case 3: theater

Figure 7 shows the results of recordings and simulations of two musical performances. 6 exits have been monitored, 4 other exits were hardly used.
Simulex shows a relatively high deviation for exit 1A and 1F. A sharp corner just before the exit as well as after the exit makes the agents only use a small part of the exit, smaller than in reality. Because buildingexodus has the option to make agents avoid a high density of occupants ('natural movement'), this effect is less and times agree better to the recordings. A small overprediction is due to modeling the ascent next to the seat rows as stairs, while in reality this is a ramp. The agents in Pathfinder also avoid places with a high density of occupants. So they use a wider part of the corner and thus of the exit. This is more in line with reality, therefore the resulting times from Pathfinder have a small deviation compared to the measured times. The large underprediction of exit 1B at performance 2 can be explained by a few people with high pre-movement time. If the pre-movement times were more averaged like assumed in the simulations the agreement is similar to other exits and performance 1.

The manual calculation show in most cases a small underprediction. This is again caused by modeling the sloped stairway of the stands as a horizontal corridor. Also sharp bends in the egress route are ignored in the simplified models.

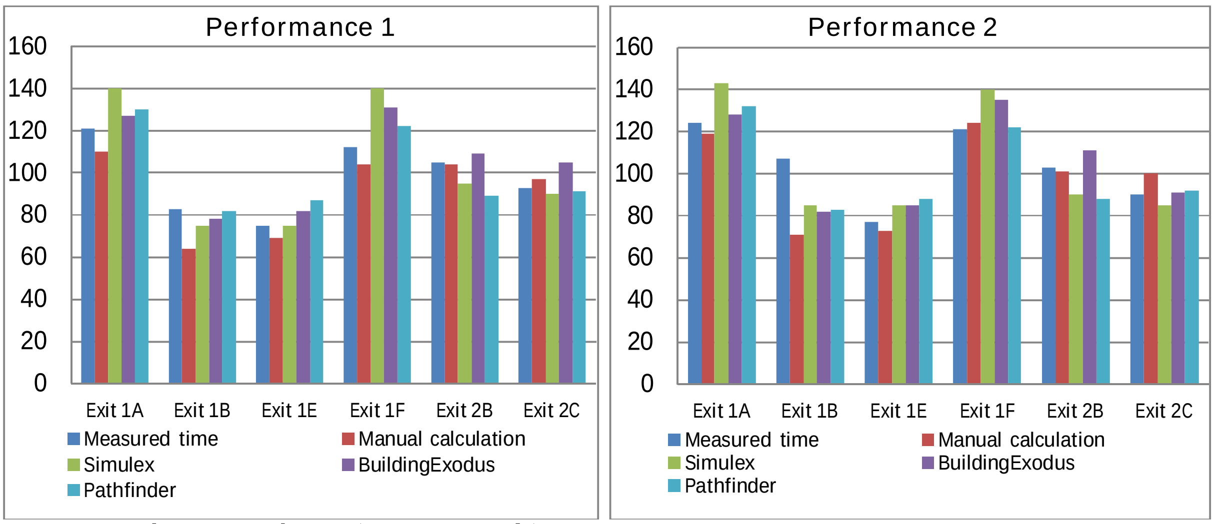

Figure 7:Results case 3 – theatre (times in seconds)

To summarize, there are several factors that lead to a difference between the recorded events and the models.

- Differences in variation/spread of pre-movement times. There is still insufficient research done to this variation/spread in an emergency situation, to give each agent a realistic pre-movement time. It is recommended to run a simulation without pre-movement time (so all the persons start simultaneously). This is a conservative approach, because this results in the largest possible congestion around bottlenecks. Afterwards an averaged pre-movement time is added to the movement time.
- The way of modeling the stairway (as stairs or horizontal corridor), combined with conservative values in buildingexodus for stair capacity by using 'stair nodes' (see also subheading stairway).
- Delays in curves or around obstacles in Simulex
- Delays by conflicts when streams merge and obstacles should be passed simultaneously in Pathfinder.

In general the models tend to overpredict egress times, making them conservative and appropriate for fire safety purposes. Nevertheless it is interesting to zoom in at specific parts of the model to see if the dynamic behavior shown in the simulations is realistic. The main issues are discussed below. This dynamic behavior is not included in the manual calculations.

BOTTLENECKS

Seat rows

Video footage

In all three cases it shows that passing each other in seat rows is not possible. If people at the end of a seat row need a longer pre-movement time, then the whole row will obtain the same pre-movement time.

Simulex

In simulex the user has no choice whether to model people standing up or sitting down, so all occupants start standing somewhere in the seat row. Because narrow corridors cause the simulex agents to get stuck sometimes, it is recommended to model seat rows as single lines, see figure 8. Agents have sufficient space then, without the possibility to pass each other.

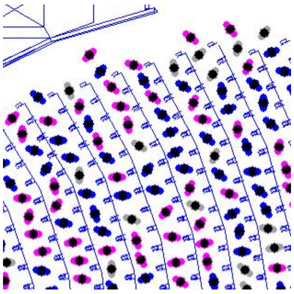

Figure 8: Seat rows in Simulex

BuildingExodus

In buildingexodus one can choose to model the stands by rows of chair nodes combined with 'free space' nodes to create an isle in front of the seats, see figure 9, left. When using varying pre-movement times, agents can walk along sitting people in this geometry, which is not realistic.

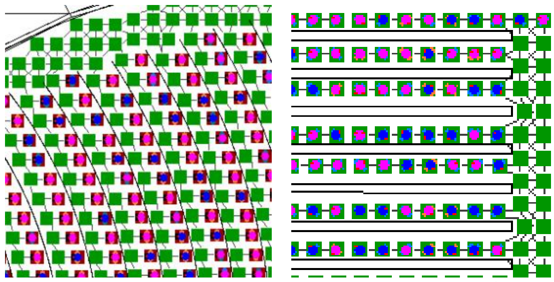

Figure 9: Seat rows in BuildingExodus, left with chair nodes and right without chairs.

The best way to model a stand in buildingExodus is therefore a single row of free space nodes, as shown in figure 9, right. The option of people jumping over seats in case of impatient behavior cannot be used in that case, but one can question the need for this option for regular fire safety engineering purposes. As mentioned earlier, it is recommended to run a simulation without pre-movement time, enabling both modeling options shown in figure 9(same results).

Pathfinder

Similar to Simulex it is not possible to model seats (people sitting down) in Pathfinder, so the occupants start standing up in the seat rows. In Pathfinder the occupants move via virtual areas, which are connected by stairs, ramps or doors. Each seat row is a different area (with a different color in the model), because of the height differences between the rows. This is shown in figure 10.

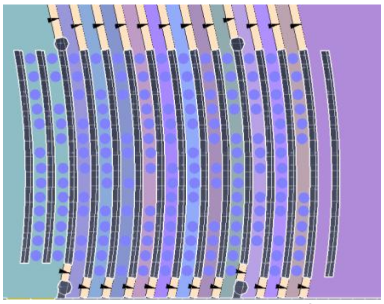

Figure 10: Seat rows in Pathfinder

The occupants cannot pass each other in the seat rows, because the modeled rows are too narrow to pass. This causes conflicts if two agents in the same row choose an opposite exit. This could happen in Pathfinder because the agents choose their exit not only based on the walking distance to the exit of the building, but also on the distance and queue time to the exit of the virtual area. In addition, the occupants change their exit choice relatively easy (making them turn around). When agents meet each other in the middle of a row, one of the agents changes his route/exit choice.

<u>Merging behavior on stairway</u>

Video footage

People leaving their seat row have to merge with the flow ascending or descending on the stairway. This merging behavior is clearly shown in the video footage; people form rows on the stairway and tend to move away from the seat rows to make space for the rows ahead of them.

Figure 11: Merging behavior on the stairway of a grandstand

Conflicts appear when people have a large drive to evacuate the stands as soon as possible. Merging seems to be going smoother when there is less urgency (or bigger difference in drive between people), for example in the sports arena case.

Simulex

In simulex the agents basically all have the same drive and moreover are eager to walk the shortest distance. This leads to many conflicts and delay, compared to the recorded events (figure 12, above). The same happens when the stairway is modeled as 'regular' stairs between floors with links representing the exit of each seat row (figure 12, below). In Simulex it is not possible to model the stairway of a grandstand as stairs with steps, because too many conflicts occur when people from the seat rows try to merge on it (the simulation crashes).

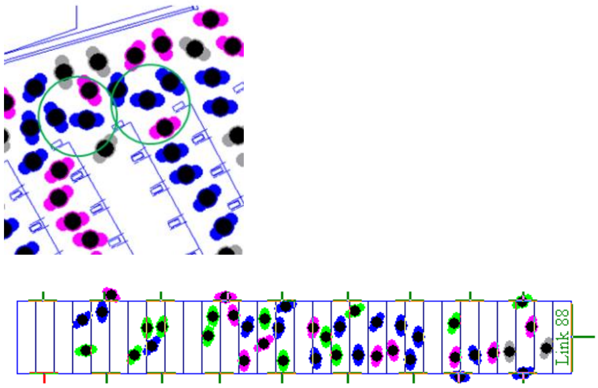

Figure 12: Merging behavior on stairways in Simulex, above; stairway modeled without stairs, below; stairway modeled as 'regular' stairs.

Pathfinder

In Pathfinder the agents basically all have the same drive too, but are less focused on the shortest route to the exit in comparison with Simulex. The agents avoid high population density and collisions. So in Pathfinder conflicts occur too when people merge, but not as many as in Simulex because the agents deviate easier from their route. The agents interact with each other to merge and to form rows on the stairway (figure 13).

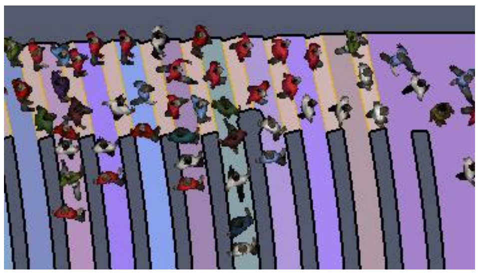

Figure 13: Merging behavior on stairways in Pathfinder

BuildingExodus

In BuildingExodus there are two options to model stairs: with stair nodes or with a transit node. Stairways on grandstands can only be modeled by stair nodes, because it is not possible to let people enter a transit node halfway. Transit nodes will therefore be used mainly for staircases.

In exodus conflicts arise if two people want to occupy the same node (one already standing on the stairway and one coming out of the seat row). The drive value, that is given to each agent, decides who will go first in that case. A certain conflict time is added to the time it takes to move to the next node. So although the conflict is not that obvious to see, the simulations in buildingexodus do not show significant differences in merging speed, compared to simulex. A phenomenon that is not realistic appears if nodes are not connected correctly. People on the stairway try to avoid conflicts by sidestepping back into a seat row (figure 14). The video footage show that this does not happen. A solution is to connect the seat rows with a single arc to the stairway, preferably in the direction of the flow on the stairway.

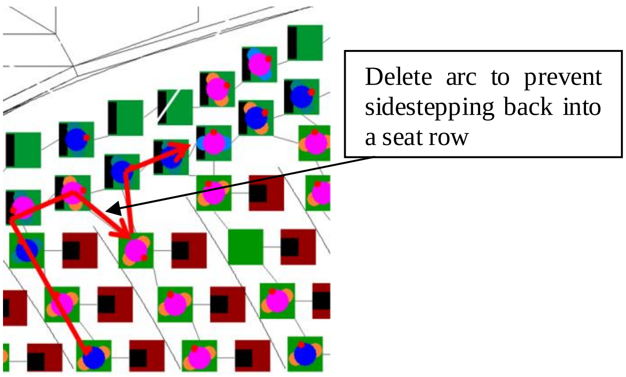

Figure 14: Connecting seat rows to stairways in BuildingExodus

Further tests show that the flow capacity on the stairway in exodus differs from 0.47 – 0.83 pers /m s, mainly depending on the usage of the 'stairpacking' option. These values roughly correspond to the flow capacity on a staircase between floors and are lower than most values found in literature. In general it is recommended to apply the stairpacking option and use normal node connections. Stair packing means that people will not try to leave free space in front of them as well as next to them. To compensate for body swing buildingexodus already assumes a distance of 0.76 m instead of 0.5 m between nodes on stairs.

Row forming on stairway

Video footage

After reaching the stairway the recordings show that people tend to form rows. Especially when two stands sections share a stairway, people stay in their own row (given that there is no acute emergency that leads to overtaking etc). Ideally this row forming is also seen in the simulations.

Simulex

Figure 15, left, show the behavior in Simulex in the lecture hall case. Clearly there are no defined rows. The effect could be forced by adding guidance lines (figure 15, right) but this should be considered as a workaround, possibly leading to loss of other (wanted) dynamic interaction..

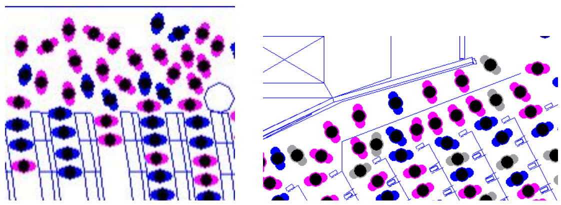

Figure 15: No row forming on the stairway in Simulex (left). Creating row forming by adding guidance lines (right).

BuildingExodus

BuildingExodus uses a orthogonal grid, automatically leading to some kind of row forming. In the simulation of the sports arena, people enter the stairway from two sides. As long as the stairway is not too crowded, agents stay in their own row, obviously resulting in the shortest distance. When there is a delay, mostly at the end of the stairway, agents switch between rows, trying to overtake the person in front of them. This effect is not seen in reality, because people look ahead and see that the other lane is not moving faster.

The sidestepping can be prevented by removing the connections between nodes that enable movement in this direction. In case of a wider stairway, it is recommended to connect nodes in a way that agents are stimulated to move to the middle of the stairway. The movement in the opposite direction, impeding people in the seat rows from moving onto the stairway is hardly seen in the video footage.

Pathfinder

In Pathfinder row forming automatically occurs, because agents divert to areas with a low population density. Near the seat rows on the stairways population density is higher because of the intercalating people from the seat rows. If occupants from the seat row want to enter the stairway the occupants on the stairway move away from the seat row side, caused by interaction between the agents. Figure 13 shows the row forming in the lecture hall modeled in Pathfinder.

Merging behavior on gallery

Video footage

In some cases, like the sports arena, the stairway leads to a wider gallery where people have to merge with a people flow in the other direction. The video footage shows that when the density on the gallery is high the flow out of the stairway is delayed, people have to make a 90 degree turn and merge at the same time. Although this phenomenon is visible at some moments, people tend to make space for the ones that come out of the stairway; when the density on the gallery is low, people on the gallery usually move away from the stairway to free some space.

Simulex

In Simulex the agents are eager to walk the shortest route and in this case that means right next to the back of the stands, causing trouble for the people exiting the stairway (figure 16, left). So even at lower densities the merging behavior is too conservative. As the behavior cannot be adjusted by the user, one should add a guidance line, forcing people to walk further from the stands, figure 16 right. Merging then happens while walking in the same direction instead of right-angled.

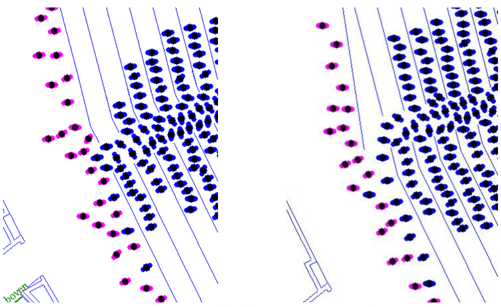

Figure 16: Merging behavior on the gallery of the sports arena in Simulex, without guidance line (left) and with guidance line (right).

BuildingEXODUS

In exodus the effect is similar but less strong (figure 17 left). When using the behavior option 'natural movement', people scatter more across the gallery, further improving the merging possibilities (figure 17, right). This last way of modeling corresponds best to the recorded behavior, because the people on the gallery are less restrictive for the people who enter from the stairway. When people on the gallery can hardly move away from the stairway, they block the stairway. The number of people from the grandstand entering the gallery reduces significantly.

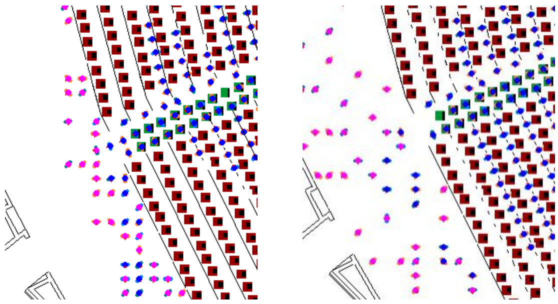

Figure 17: Merging behavior on the gallery of the sports arena in BuildingEXODUS, without using behavior option 'natural movement' (left) and with using 'natural movement' (right).

Pathfinder

In Pathfinder the people on the gallery give the intercalating people space. When the people on the gallery come close to the people from the grandstands they deviate from their route. This is caused by interaction between the agents in combination with trying to avoid high population density and collisions. In figure 18 (right) the persons are shown as green arrows, pointing in their walking direction. The figure shows the deviation from their route by the persons on the gallery.

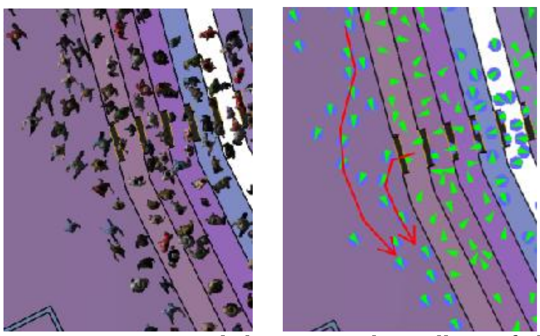

Figure 18: Merging behavior on the gallery of the sports arena in Pathfinder, the people shown as real persons (left) and as arrows (right).

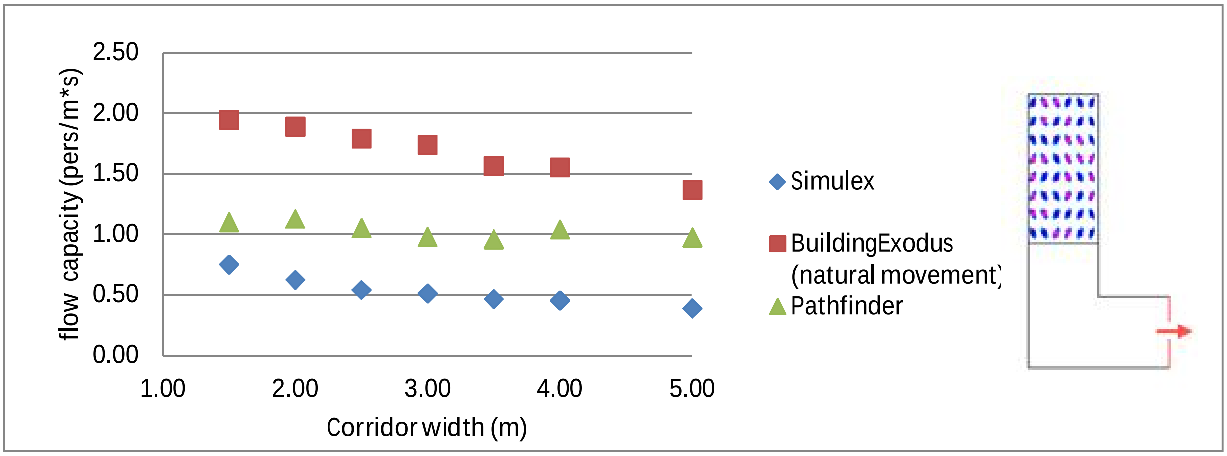

Figure 19: Flow capacity of curves in Simulex, BuildingExodus and Pathfinder

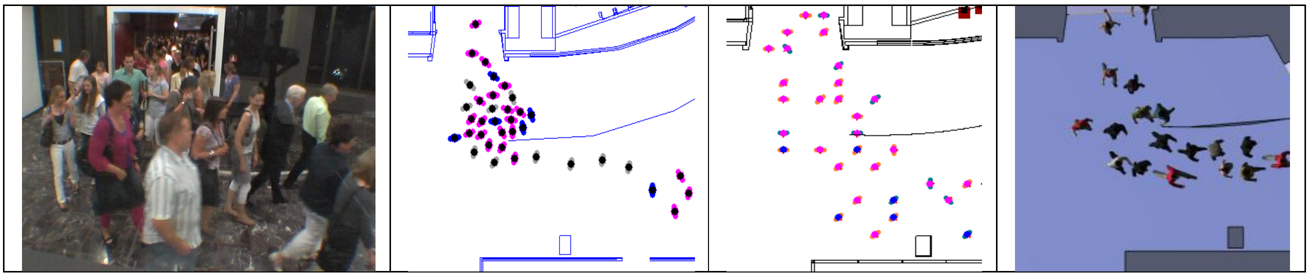

Figure 20: People passing a curve (from left to right: video footage, Simulex, BuildingEXODUS and Pathfinder)

Curves

Sudden changes in direction, like a 90 degree turn in a corridor, is one of the geometries that lead to differences in results. Especially in Simulex the urge to cut corners in order to walk the shortest distance seems to be too big. In buildingExodus and Pathfinder this effect is less. Also, one of the behavior options in buildingexodus enables the user to enforce a more natural movement. This option in BuildingExodus provides a even bigger used floor area in the curve than Pathfinder. A simple testcase of a 90 degree turn with variable width shows the difference between the three models (figure 19).

It shows that the flow capacity per m tends to decrease as the width increases. In other words, a smaller percentage of the curve is used effectively.

The recordings do not lead to a reliable measurement of flow capacity in corners, but the preference for the inside corner is obvious. The models of buildingExodus and Pathfinder give the best accordance with the recorded images, this is shown in figure 20. So a realistic flow capacity seems to be a value between 1.8 – 1.0 persons / s · m corridor width for corridors up to 5 m wide. Using Simulex, the performance can be somewhat improved by adding guidance lines in the corner, though this decreases the basic interaction between agents, as mentioned before, and should only be done if clearly unrealistic flow exists.

MAIN CONCERNS PER MODEL

By using the manual calculation it is recommended to use conservative input values, because dynamic behavior is not included in these calculations. This means that potential delay due to curves and merging behavior is not taken into account.

There are two main concerns of Simulex:

- People have a strong preference for the shortest route, this has a negative influence on the flow capacity, especially in curves.
- People may get stuck in the simulation when passages are too small. People get stuck against each other or against walls (or guidance lines).

The performance in Simulex can be improved to a certain extent by adding guidance lines. The use of these lines should be limited, because it decreases the basic interaction between agents.
Furthermore, the people in the simulation should always have enough space to move, also between the

guidance lines. This is particularly an issue when modeling seat rows.

To get the most realistic movement in BuildingExodus, the behavior option ‘natural movement’ should be used. With this option the agents avoid a high density of occupants, leading to more realistic behavior in curves and merging flows. Also the option ‘stairpacking’ should be used, to get the most realistic movement on stairways. These stairways should be modeled with ‘stair nodes’ (it is not possible to model them with ‘transit nodes’). BuildingExodus assumes a distance of 0.76 m (instead of 0.5 m on a flat surface) between stair nodes, to compensate for body swing on stairs.
Further, in BuildingExodus people on the stairway try to avoid conflicts by sidestepping back into a seat row, this does not happen in reality. To prevent sidestepping back into a seat row, each seat row should be connected with a single arc to the stairway.

When using “Steering mode” in Pathfinder, interaction appears between the agents. This movement simulation mode shows the most realistic movement in Pathfinder. The people choose a route based on the distance to the final exit and the exit of the current ‘room’ (virtual area). Besides, the waiting time in a queue for an exit of the current virtual area is taken into account at the exit selection. So occupants move from virtual area to virtual area, this means on a grandstand from row to row. For a realistic distribution of the occupants over the exits, one can use the option to give stairs a required direction. This also prevents occupants to move in an opposite direction on a stairway. This sometimes happens because the occupants in Pathfinder change the desired exit / route relatively soon, mainly caused by the queue time. To prevent excessive route switching, the default door preference value should be increased (value determining the drive to stick to the initially chosen door).

It is recommended to run a simulation without explicit pre-movement time, because there is still insufficient research available to the variation/spread of the pre-movement time for different populations. A conservative but realistic averaged pre-movement time should be added to the total movement time.

Finally, it is well known that for all simulation software the distribution of persons over the exits has to be user-controlled. This also follows from the simulations done in this research. None of the programs guarantees a realistic distribution immediately in any situation.

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