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USING CASE STUDY DATA TO VALIDATE 3D AGENT-BASED SIMULATION TOOL FOR EGRESS MODELING

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ABSTRACT

This paper describes how data collected from observed evacuation drills were used to validate the 3D agent-based pedestrian simulation tool, MassMotion, for egress modeling. MassMotion employs 3D environments and behavioral profiles to model and analyze pedestrian movements and route choice. Based on industry standard metrics, the behavioral profiles enable agents to make a series of choices that lead them to their destinations. Agents have the ability to recognize and respond to elements such as congestion, signage, route closings and other dynamic changes.

MassMotion has been applied to a wide array of applications including rail, building, infrastructure and urban design projects. Through these projects, MassMotion has demonstrated that it can be a common platform for modeling normal peak pedestrian flows, and for producing high quality visualizations. While MassMotion has gained acceptance in the realm of pedestrian planning and design, the field of fire engineering requires a more robust validation process specific to egress modeling in order for the platform to be applied to egress projects.

The research team conducted a series of validation exercises using data collected from evacuation drills held in four different high-rise buildings; three located New York City and one in London. Validation metrics used in this study varied from case to case based on available data, but in each instance modeled evacuation time was compared to observed evacuation time. Other validation metrics include journey times, speeds and flow rates as well as observations of behaviors such as crowding and queuing.

The results from the validation exercises indicate that MassMotion is a suitable application for egress modeling, producing total evacuation times that were between 1% and 10% different than observed times. Additionally, agent movements and behaviors corresponded well to observations.

This application of MassMotion aligns transport and fire egress modeling methods, encouraging collaboration between the two fields and increasing efficiencies in combined use models. Given the capability of the agent-based model, egress models built in MassMotion can be used to test scenarios and make recommendations for safety preparedness improvements.

INTRODUCTION

The functionality of MassMotion, Arup's pedestrian micro-simulation tool, has developed to the point that it is comparable to other commercial simulation packages in terms of its functionality, ease of use and reporting capabilities. Its use and application has expanded beyond rail stations to include a wide array of building, infrastructure and urban design work. Through these projects, MassMotion has demonstrated that it can be a common platform for modeling normal peak pedestrian flows and for producing high quality visualizations, all based on standard architectural/engineering 3D CAD. Despite these advancements, MassMotion has not yet gained acceptance within the fire engineering business as an appropriate tool for egress modeling because it has not been specifically validated for this use.

Recognizing the need, Arup launched a two-phase validation exercise to examine the MassMotion simulation package's potential for egress modeling:

- Phase 1 – Arup New York office building evacuation drill; and
- Phase 2 – Full-building evacuation drills of three different office buildings.

Each model was calibrated based on available population counts, videos and behavioral observations gathered during evacuation drills. Emergent model properties such as journey times and flow rates were used to test the validity of each model. General movement and behavior patterns were visually validated.

The first phase of this exercise consisted of a model of Arup's New York office, using data collected during a 2009 evacuation drill. A comparison of observed to modeled total building evacuation time shows that the MassMotion model produces accurate results – a 5.6% difference between modeled and observed. Agent movements and behaviors were similar to those observed and did not produce any unexpected actions. The second phase of the exercise consisted of models of three full building evacuations: 10 Hanover Square, 85 Broad Street and One Canada Square. Two models of buildings in Lower Manhattan (10 Hanover Square and 85 Broad Street) were created with data from prior Arup Fire Team work including observations from full building evacuations in 2001 and 2002. The third building, One Canada Square in London, was part of a previous MassMotion validation exercise in 2007.

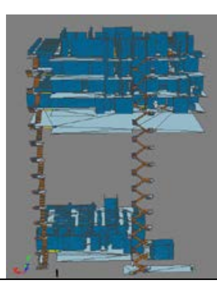
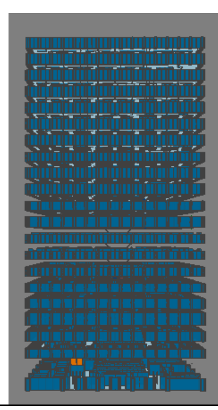
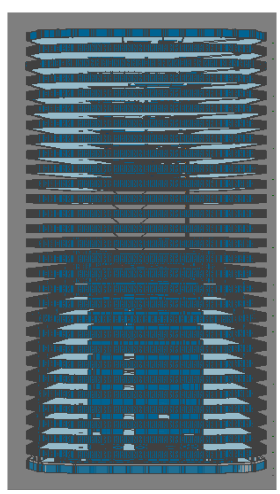
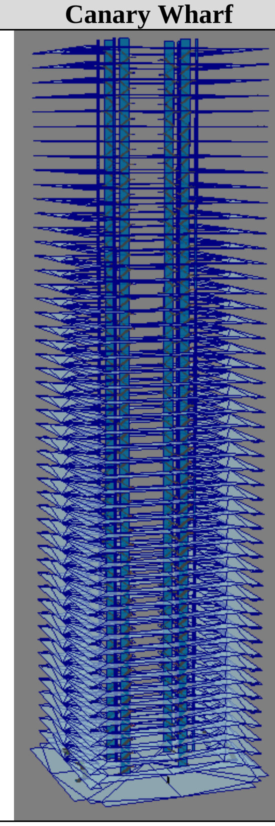
Table 1 describes the four models created as part of this validation exercise, the sum of which represent a range of building scale and population to analyze MassMotion's capability of modeling egress scenarios. Comparisons of observed to modeled total building evacuation time indicate that MassMotion produces results within an acceptable range – from 1% to 10% different than observed times.

ABOUT MASSMOTION

MassMotion is founded on the construction of behavioral profiles for agents, and the construction of a 3D environment for these agents to occupy. Each agent is provided with an origin and destination (O-D) at the outset of the micro-simulation. Each agent makes a series of choices to arrive at their destination based on their O-D pair and behavior profile. Agents have the ability to recognize congestion and will consider alternative routes based on their familiarity with the environment, adapting to current conditions.

The 3D environment used in MassMotion can be constructed in Autodesk Softimage or imported from industry standard CAD and BIM tools. Agent behavior profiles are based on accepted values including those researched and documented by John J. Fruin in his book *Pedestrian Planning and Design* (Fruin 1971). A variety of original data sets including evacuation and route choice surveys also inform the behavior profiles. MassMotion provides outputs of critical statistics such as population counts, journey times, flow rates, and agent speeds. MassMotion v4.1 was used for the egress validation exercise.

Table 1: Buildings Used for Validation of MassMotion for Egress Modeling

155 Avenue of the Americas	**10 Hanover Square**	**85 Broad Street**	**One Canada Square, Canary Wharf**
			
Floors: 15 (6 modeled) Evacuees: 232	Floors: 22 Evacuees: 1,130	Floors: 30 Evacuees: 1,385	Floors: 50 Evacuees: 5,469 (53% stairs)

Agent Movements and Decision Making

MassMotion divides crowd movement calculations into two distinct processes: reflexive and contemplative. The reflexive component governs the agents' basic movements and responses to the environment. The movement of individual agents in MassMotion is based on a social forces algorithm modified for MassMotion (Helbing 1995). The social forces model represents individuals as objects which have a number of forces acting upon them including goal, obstacle, and neighbor forces.

The contemplative component of crowd activity is concerned with network path planning between origins and destinations. This component enables agents to analyze distance, congestion and terrain, develop costs for routes available to the agent's goal, and select the most appropriate route. The simplified algorithm for total route cost is provided in Equation 1.

Equation 1: Simplified Route Cost Algorithm

$$cost = W_D * \left(\frac{D_G}{V}\right) + W_Q * Q + W_L * L$$

Where,

- W_D = Distance weight (random agent property)
- D_G = Total distance from agent position to ultimate goal
- V = Agent's desired velocity*
- W_Q = Queue weight*
- Q = Expected time in queue before reaching link entrance
- W_L = Link traversal weight*
- L = Link Type Cost (level, ramp, stair, etc.)

*Randomly applied to agents from a distribution

Agent Speed Profiles

Every agent in MassMotion has a randomly assigned natural walking speed. The default agent speeds are normally distributed in a range from 2.1 to 6.7 feet/second with a standard deviation of 0.5 feet/second (Peacock et al. 2010). Agents adjust their speeds based upon congestion as well as the type and slope of the surface being traversed. Agent speeds on stairs are prescribed within MassMotion based on Fruin's speed profiles as shown in Table 2. Note that the described speed refers only to the horizontal speed and does not include the vertical component.

Table 2: Fruin Observed Stair Speeds

Surface Type	Direction	Angle (Degrees)	Avg. Speed (ft/min)
Stair	Up	27	113
Stair	Up	32	100
Stair	Down	27	152
Stair	Down	32	132

Based on Fruin's observed speeds, MM assigns agent stair speeds as a function of the flat surface natural walking speed. For example, an agent moving up a staircase with a 27 degree angle (or less) will move at an average of 113 feet per minute if their natural flat walking speed is 265 feet per minute. For stairs between 27 and 32 degrees, speeds are interpolated between those values described by Fruin. For example, agent speeds on a 26 degree angle will move at a maximum of 42.6% of its natural walking speed. The agent speed inputs for MassMotion are detailed in Table 3.

Table 3: Agent Stair Speeds in MassMotion

Surface Type	Direction	Angle (Degrees)	Percent of Natural Speed
Flat	N/A	0	100
Stair	Up	$0 < X < 27$	42.5
Stair	Up	$27 \leq X \leq 32$	Interpolated between 42.6 and 37.8
Stair	Up	$32 < X$	37.8
Stair	Down	$0 < X < 27$	57.4
Stair	Down	$27 \leq X \leq 32$	Interpolated between 57.4 and 49.8
Stair	Down	$32 < X$	49.8

VALIDATION EXERCISES

Validation Metrics

Validation criteria for fire egress software platforms have been described in technical and research papers, but these often combine the concept of calibration and validation into one category without suggesting standardized acceptance levels for validation.

A summary of Project 3-46 by the National Cooperative Highway Research Program for modeling unsignalized intersections, best describes the approach taken for the egress validation exercise: "Model validation is the testing of a calibrated model using empirical data that were not used to initially calibrate the model" (Kyte et al. 1996). Further to this, London Underground Limited (LUL) uses a Best Practice Guide for station modeling with Legion pedestrian simulation software (London Underground 2009). This guide addresses principles and thresholds for demonstrating validity:

- Journey times on key routes and pedestrian flow counts taken at key locations should act as main elements for validation;
- The simulated journey times of key routes should correspond with the surveyed journey times, and be within 10% of the latter; and
- It is possible to use visual validation by comparing model entity movements and observations in [the] station.

The three LUL principles are addressed within this egress validation exercise. Outputs for journey times and link flows were extracted from the simulation and analyzed. In the following sections, model results are compared with observed counts.

Validation Exercise #1: 155 Avenue of the Americas, New York

Evacuation Drill

A scheduled evacuation drill of the New York Arup office building at 155 Avenue of the Americas was held on October 27th, 2009. The drill included all six floors housing Arup employees (2nd, 10th, 11th, 12th, 13th, and 14th) and required staff to evacuate using the building's two stairwells, Stairwell X in the front of the building (East side) connecting to the main lobby and Avenue of the Americas, and Stairwell Y in the rear (West side) connecting through a corridor to Spring Street. This drill provided the opportunity for Arup to collect egress data from each of its floors to then be used as inputs to a MassMotion model.

Data Collection

Two methods were employed to collect data during the evacuation drill:

- Video, to disseminate journey times, individual movements and behaviors; and
- Manual counts, to provide occupancy and flow data.

Four digital video cameras were set up to capture behavior and movements during the evacuation. A camera was located in each stairwell just beyond the two internal exits on the 11th floor. These cameras were placed close to the ceiling in order to capture a top-down view of people as they traversed the stairs thereby allowing the study team to track movements and behaviors. Two additional cameras were placed at the street level exits to capture people as they exited the building. The building owner provided the survey team with video from internal security cameras focused on the front lobby.

Manual counts were taken at the internal exits on each office level at 30 second intervals. Counters were directed to stand in the lobby, out of the way of those evacuating so as not to interfere with the flows. Each counter took note of the number of people exiting the floor as they crossed through the doorway into the stairwell. Therefore, these counts only consider the number of people through each occupied floor and do not include evacuees from higher floors. Standardized forms were distributed to counters at a strategy meeting to ensure a uniform method of data collection.

Total Evacuation and Movement Time

The total time for escape from an area can be expressed as a combination of detection and notification time, pre-movement time, and travel time, demonstrated in Equation 2. The data collection exercise encompassed the entire evacuation time process, from the fire alarm through to exit. The calibration and validation processes focused on the total evacuation time and the movement time.

Equation 2: Total Evacuation Time

$$t_{eva} = t_o + t_{pre} + t_{mov}$$

Where,

t_{eva} = the total time for evacuation
t_o = the detection and notification time
t_{pre} = the pre-movement time (includes response and recognition time)
t_{mov} = the movement time (queuing time or travel time)

Building Population

The number of evacuees observed during the evacuation drill consisted of about 77% of the total Arup staff located within the building. This proportion is generally what the survey team expected given employee absences (vacation, travel, meetings, illness, etc.) and some observations of employees departing the building prior to the alarm in order to avoid the rush. A total of 232 employees were observed evacuating during the drill; 162 used Stairwell X and 70 used Stairwell Y.

Model Building

Existing 2D AutoCAD files of the Arup New York office building were converted into 3D files for importing to Softimage. These layers were then modified to make the CAD properties recognizable to MassMotion agents. Using the MassMotion interface, geometry pieces were classified as floors, stairs, links (between floors), and barriers. Additional objects were created and defined as portals, serving as entrance and exit points. Origin-destination demand profiles were then added to each of these portals to create populations for each floor. Once the base model was completed, its geometric elements and data inputs were authenticated to be error free, and then exported in order to run the simulation. The model was calibrated to the observed counts to ensure that it provided an accurate representation of the evacuation drill.

Model Results: Total Evacuation and Journey Times

Randomly generated seeds were used to run ten models. The results of the ten models were averaged for reporting final results. Video observations were used to gauge journey times for a sample of evacuees in each stairwell. These journey time observations were compared to modeled journey time outputs for all agents as a validation metric. Collected journey times include:

- Total building evacuation time (time from alarm sound until the last employee exited the building); and
- Individual stairwell journey time (time from when an individual crossed the 11th floor stairwell landing to the moment at which that individual exited the building).

The total evacuation time produced by the MassMotion model was 7 minutes and 49 seconds, 5.6% less than the observed evacuation time of 7 minutes and 24 seconds.

Table 4 shows the average of modeled journey times as compared with the observed travel times extracted from video.

Table 4: Comparison of Observed and Modeled Journey Times from 11th Floor to Exit

Scenario	11X to Exit (mm:ss)	11Y to Exit (mm:ss)
Observed: Average of Samples	2:59	2:16
Modeled: Average of All Agents	3:39	3:04
Difference from Observed	22.4%	35.1%

The model overestimates the journey times for agents using Stairwell X by 22% and agents using Stairwell Y by 35%. The difference in individual stairwell journey times could be caused by a difference in population sets from the Arup building evacuation drill and the MassMotion default agent stair speeds. The modeling team postulates that the building's population may be more homogenous and representative of a younger and/or fitter population than the general public, which would manifest as slower individual journey times in the models.

The highest sampled individual journey time on Stairwell Y was 2:38 which is less than the average overall modeled journey time of 3:04. Assuming MassMotion is functioning correctly, this result could mean that in an uncongested evacuation situation, people walk down stairs more quickly than observed by Fruin and therefore the speed profile inputs to MassMotion would be too slow. In this case though, congestion ceases to become a driving factor in journey time. Following from this, in a full building evacuation scenario, congestion and queuing at stairwell doors and on stairs would become the driving factor and would override the stair speed issue. This finding requires further investigation.

Model Results: Flow Rates

Video recorded during the evacuation drill was used to calculate observed flow rates through exit doors and on stairs which were then compared to modeled flow rates. Video from the 11th floor stairwells showed that at the busiest and most crowded times, the rate of people moving down the stair achieved 43 people per minute (or 12 people per foot per minute on the ~44-inch stair). Stairs can typically handle up to 17 people per foot per minute at high densities. This finding indicates that the building population (and therefore stairwell occupancy) was not high enough to achieve the upper limit of density or flow. As such, validation based on stairwell throughput at the limits of occupancy cannot be demonstrated for this study. However, a comparison of maximum achieved flows to maximum modeled flows can be established.

Peak flows on stairs and at the ground floor exits were extracted from the models in 15-second intervals to confirm they were correct compared to observed flows. The modeled maximum flow of people per 15-second interval on Stairwell X on the 11th floor was 15 people, compared to the observed maximum flow of 14 people per 15-second period.

Figure 1 compares modeled flows (an average of ten model runs) of evacuees exiting the front stairwell to flows observed on film. Overall, the model generally follows the curve of observed exit flows. Discrepancies between modeled and observed flows may be partially explained by the uncertain and therefore inaccurate replication of pre-movement time. In an attempt to reduce this uncertainty in the comparison, data from the models was set to align with observed data. Specifically, the time the first model agent exited at ground floor was aligned with the time the first observed evacuee exited at ground floor. One possibility to completely eliminate the pre-movement time would be to generate agents directly at the stairwell exits, then compare to observations beginning when the first evacuees enter the stairwell.

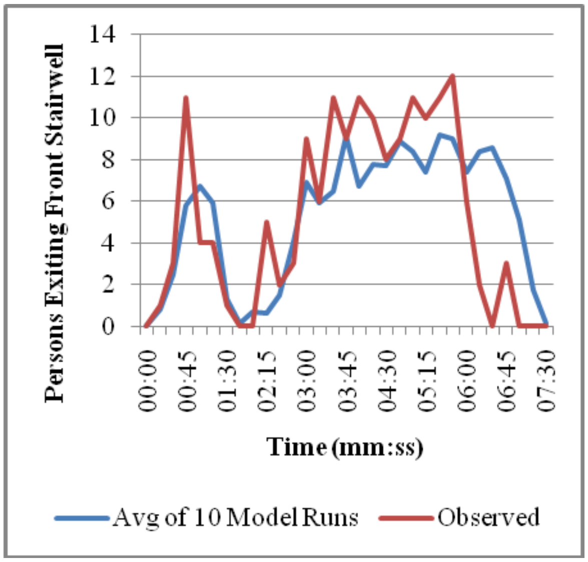


Figure 1: Comparison of Modeled and Observed Flow Rates on the Front Stairwell Exit

Figure 2 compares the modeled and observed cumulative number of persons exiting via the front stairwell. The curve demonstrates that the model mimics the observed flows, but is slightly slower.

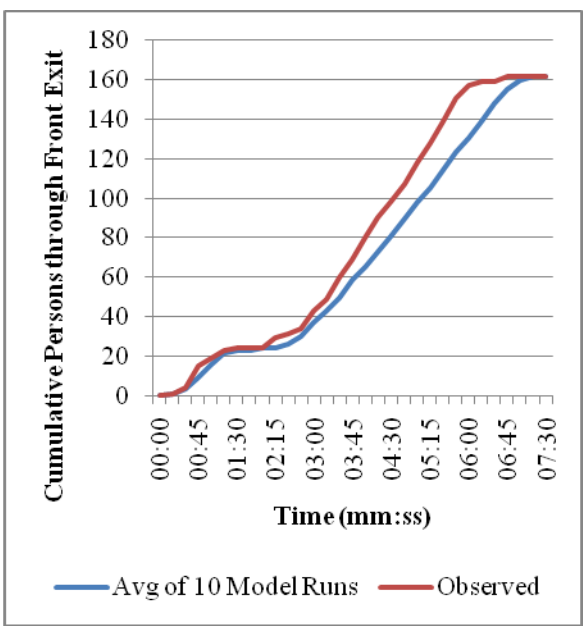


Figure 2: Cumulative Number of Persons through Front Exit

Figure 3 compares the modeled and observed cumulative number of persons exiting via the rear stairwell. Similar to the curve for the front exit flows, the curve for the rear exit flows demonstrates that the modeled flows are generally in line with observed flows through the peak evacuation period, though slightly slower at representing the tail end of each exiting group.

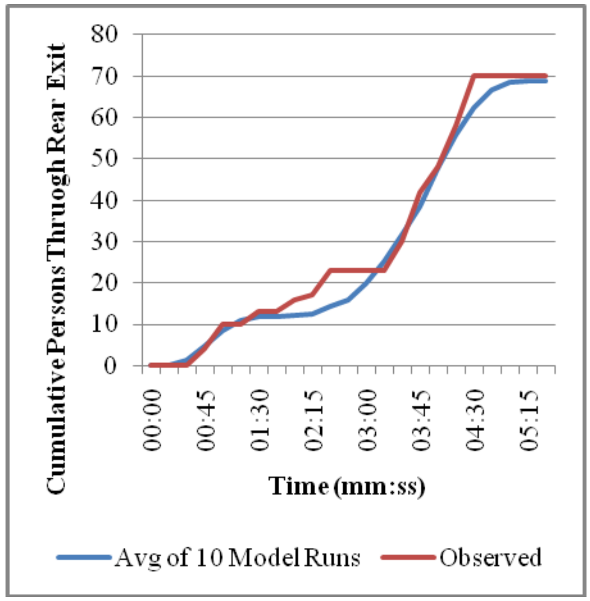


Figure 3: Cumulative Number of Persons Through Rear Exit

Summary of Validation Exercise One: 155 Avenue of the Americas, New York

It is the opinion of the modeling team that the MassMotion evacuation model represents a very good correlation to the observed egress data. The average total evacuation time produced by 10 MassMotion models was 7 minutes and 49 seconds, 5.6% less than the observed evacuation time of 7 minutes and 24 seconds. Additionally, modeled link flows on the 11th floor stairwell and at the exits corresponded to observed flows. Individual journey times and flows at ground floor exits were consistently slower than observed, though it is assumed that this is partially due to a faster egress population.

While the model produced positive results regarding MassMotion's ability to simulate egress scenarios, further validation exercises were needed, particularly those involving models of full-building egress scenarios.

Validation Exercise #2: 10 Hanover Square, NYC

Evacuation Drill

The tenant of the office building at 10 Hanover Square in New York City conducted a full-building evacuation in May of 2002. The evacuation consisted of 1,130 people and lasted approximately 13 minutes from alarm sounding to when the searchers declared the evacuation complete. Observations and counts were recorded on the first floor of the building.

Building Layout and Population

The 22-story building contains two stairwells that extend from the 22^{nd} floor to the 1^{st} floor. Two ground floor exits were available on the day of the evacuation drill, the main exit on the south side of the building and a secondary exit on the west side of the building. In addition to the two stairwells, the building contains a set of escalators that connect the 1^{st} and 2^{nd} floors. CAD drawings of the building were used to inform the egress model geometry.

Total building occupancy at the time of the evacuation was 1,130 people, approximately 35% of the full building occupant load. Observations indicate even distribution among the two stairwells. During the evacuation drill, fire wardens located on the second floor directed approximately 35% of the evacuees from the 2^{nd} floor stairwells to the escalators in order to ease congestion.

Model Results: Journey Time

Randomly generated seeds were used to run ten models. The results of the ten models were averaged for final results reporting. The MassMotion models produced an average overall evacuation time of 13 minutes and 11 seconds, a 1.4% difference from the observed evacuation time of 13 minutes.

Validation Exercise #3: 85 Broad Street, NYC

Evacuation Drill

The tenant of the 85 Broad Street New York office building conducted a full-building evacuation in June of 2002. The evacuation consisted of 1,385 people and concluded in approximately 18 minutes. Counts and observations were conducted on the first floor of the building during the evacuation drill.

Building Layout and Population

The building at 85 Broad Street consists of 30 stories (Floor 1 – Floor 31, skipping Floor 13), a concourse, and a sub-concourse. The building is served by three stairwells; Stairs A and B are fire stairs while Stair C is a “tenant interior” stairwell. Stair A is located on the west side of the building and Stair B is located on the east side of the building while Stair C serves the center of the building. Stair C runs from the 30th Floor to the Concourse. On the 2^{nd} Floor, occupants must exit Stair C and enter a separate portion of Stair C to access the lower floors. Two-dimensional CAD drawings of the building were extruded and then imported into MassMotion to inform the geometry of the model.

The evacuation drill took place after the end of the trading day, and 1,358 employees were observed leaving the building prior to the start of the drill. Total building occupancy at the time of the evacuation was 1,385 people, approximately 22% of the full building occupant load of 6,164. For modeling purposes, occupancy per floor is estimated as a percentage of full occupancy based on the overall number of persons counted during the evacuation. The model was calibrated to the observed stairwell distributions, provided in Table 5.

Table 5: Observed Stairwell Distributions

Stairwell	Number of Evacuees
Stair A	706
Stair B	626
Stair C	57
Total	1,385

Model Results: Journey Time

Randomly generated seeds were used to run ten models. The results of the ten models were averaged for final results reporting. The MassMotion models produced an average overall evacuation time of 16 minutes and 41 seconds, a 7.3% difference from the observed evacuation time (not including fire wardens) of 18 minutes.

Validation Exercise #4: Canary Wharf, London

Evacuation Drill

On 30 October 2001 at 11:00am, a full scale simultaneous evacuation exercise of One Canada Square was completed, using all stairs and elevators located within the building. A total of 5,469 occupants were involved with the exercise. The total evacuation time was 20 minutes with the major stair flows diminishing substantially by 18 minutes.

The evacuation exercise of One Canada Square was fully monitored by Canary Wharf Management Limited (CWML) and Arup Fire. The evacuation was monitored and data was collected to allow for comparisons with other studies including hand calculations and computer modeling that was carried out prior to and after the exercise.

Four Arup Fire personnel walked down each stair core, monitoring evacuee behaviors. Their starting locations were:

- Level 5 of the Southwest core
- Level 19 of the Northeast core
- Level 34 of the Southeast core
- Level 50 of the Northwest core

Additionally, four Arup Fire personnel were located at the concourse level (discharge level for stairs) and were responsible for counting the people using the stairs and determining flow rates. One person was located in each of the core concourse areas. CWML security personnel were also positioned in the concourse areas. Video recording took place on two levels, Level 33 and 46.

STEPS Model

In 2007, a STEPS model of the Canary Wharf building was built based on the occupant loads and data collected in the full-building evacuation drill. The STEPS model was based on the geometry of the building. An occupant load of 2,939 occupants was used for the simulation with occupants split evenly between floors. Walking speeds were specified as the following:

- Horizontal walking speed – 199 ft/min (101 cm/s)
- Vertical walking speed – 98 ft/min (50 cm/s)

The total evacuation time calculated by the model was 17 minutes. As stated above, the actual recorded evacuation time during the exercise was 20 minutes with the majority of pedestrians having evacuated by 18 minutes.

While this STEPS model was not directly used for inputs into or calibration of the MassMotion model, it is interesting to benchmark the results of the STEPS models for comparison.

Building Layout and Population

One Canada Square is a 50 story office building. The highest office floor, Floor 50, is situated 660 feet (201 m) above the ground floor and the lowest, Floor 5, is approximately 60 feet above the ground floor. The building is served by four banks of eight passenger elevators (total 32 elevators) located in a series of four cores throughout the building. One bank of elevators serves each floor. In case of an emergency, four staircases, located in a central core, provide means of escape. Two of the staircases are fire-fighting shafts each with a fire fighting elevator. In addition, there are two goods elevators. Passenger elevators were used for the evacuation exercise, but the fire and goods elevators were not.

People evacuating using the stairs follow the stairs to concourse level, one story below ground, where they discharge into a protected corridor that leads to a staircase that rises up to discharge at ground level at the building perimeter.

At the completion of the exercise, the actual number of people that left the building was 5,469 which included 2,939 people using the four stairs and 2,530 people using the 32 passenger elevators.

CWML recorded a population number of 5,576 people for the exercise. There is a difference of 107 persons with the participating population due to the number of assistants and security personnel that did not evacuate the building. The total maximum population of the building was estimated by CWML to be approximately 7,500.

Counts were not conducted for every floor, so the occupancy per floor in the model is evenly distributed across all floors. The model was calibrated to the observed stairwell distributions.

Model Results: Journey Time

Randomly generated seeds were used to run ten models. The results of the ten models were averaged for final results reporting. The MassMotion model produced an overall evacuation time of 21 minutes and 53 seconds, a 9.5% difference from the observed evacuation time of 20 minutes.

CONCLUSIONS

The results from the validation exercises of four buildings of different scales, occupant loads and locations indicate that MassMotion is a suitable application for egress modeling, producing total evacuation times that are within 1% to 10% of observed total egress times, as shown in Table 6. Additionally, agent movements and behaviors on egress stairs and through doors corresponded well to observations.

Table 6: Summary of Results

Building	Scenario	Total Evacuation Time (mm:ss)
155 Avenue of the Americas	Observed	7:24
	Modeled	7:49
	% Difference	+ 5.6%
10 Hanover Square	Observed	13:00
	Modeled	13:14
	% Difference	+ 1.4%
85 Broad Street	Observed	18:00
	Modeled	16:41
	% Difference	- 7.3%
Canary Wharf	Observed	20:00
	Modeled	21:53
	% Difference	+ 9.5%

Individual journey times in the MassMotion model of the Arup New York building are generally slower than observed journey times, though the specific cause for this result has not been determined. The modeling team postulates that the building's population may be more homogenous and representative of a younger and/or fitter population than the general public, which would manifest as slower individual journey times in the models. This hypothesis could be further tested with additional data sets.

This application of MassMotion aligns transport and fire egress modeling methods, encouraging collaboration between the two fields and increasing efficiencies in combined use models. Given the capability of the agent-based model, egress models built in MassMotion can be used to test egress and evacuation scenarios and make recommendations for safety preparedness improvements.

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