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Using case study data to validate 3D agent-based pedestrian simulation tool for building egress modeling

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Abstract

MassMotion is an agent-based pedestrian simulation tool which employs 3D environments and behavioral profiles to analyze pedestrian movements and route choice. This paper describes how observed evacuation drills were used to validate MassMotion for tower building egress modeling. Validation metrics include modeled evacuation time, journey times, speeds, flow rates, and behavioral observations. The results indicate that MassMotion is a suitable application for tower building egress modeling, producing total evacuation times between 1% and 10% of observed times.

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1. Introduction

MassMotion is a pedestrian micro-simulation software platform developed over a number of years by staff at the global planning and design firm Arup. MassMotion is utilized for pedestrian planning and evacuation modeling and is available commercially through Oasys (2014). MassMotion replicates 3D spaces and people through a series of actors (agents) who interact with each other and their environment to model various different crowd simulation scenarios.

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Various components of MassMotion have been validated through a rigorous battery of tests of corridor widths, doorways, stairs and escalators, Oasys (2014). These tests isolate independent variables to verify a comparable fit between model input and model output. Other tests have been used to validate MassMotion for peak period crowd scenarios.

This paper presents an approach of using four case studies to validate MassMotion for use in egress modeling scenarios for mid-rise and high-rise tower buildings. In each case study, a model was built and 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 former New York office, using data collected during a 2009 evacuation drill. 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 (Hanover Square and Broad Street) were created with data from prior Arup Fire Team work including observations from full building evacuations in 2001 and 2002. The final building, One Canada Square in London, was part of a previous MassMotion validation exercise in 2007.

These towers 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.

2. About MassMotion

MassMotion (MM) 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 MM 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.

2.1. 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 MM is based on a social forces algorithm modified for MM, (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.

$$cost = W_D \cdot \left(\frac{D_G}{V}\right) + W_Q \cdot Q + W_L \cdot L \qquad (1)$$

where W_D is the distance weight, D_G is the total distance from agent position to ultimate goal, V is the agent's desired velocity, W_Q is the weight of the queue, Q is the expected time in queue before reaching link entrance, W_L is the link traversal weight and L is the link type cost (level, ramp, stair, etc.). Here, W_D, V, W_Q and W_L are randomly applied to agents from a distribution.

2.2. Agent speed profiles

Every agent in MM 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 MM based on Fruin's speed profiles as shown in Table 1. Note that the described speed refers only to the horizontal speed and does not include the vertical component. 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.

Table 1. Stair speeds by Fruin observed and MassMotion agents.

Surface Type	Direction	Angle (Degrees)	Fruin Avg. Speed (ft/min)	MassMotion Agent Speed as a Percentage of Natural Speed (%)
Stair	Up	0 < X < 27	-	42.5
Stair	Up	27	113	
Stair	Up	27 < X < 32	-	Interpolated between 42.6 & 37.8
Stair	Up	32	100	-
Stair	Up	32 < X	-	37.8
Stair	Down	0 < X < 27	-	57.4
Stair	Down	27	152	
Stair	Down	27 < X < 32	-	Interpolated between 57.4 & 49.8
Stair	Down	32	132	
Stair	Down	32 < X	-	49.8

3. Validation exercises

3.1. Validation processes and 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. In addition, validation is often combined or confused with verification. In this paper, calibration is assumed to be the process by which a specific variable in a model scenario is refined to match individual and measurable pattern observed in actual conditions. Similar to International Maritime Organization guidelines, IMO (2007), verification is referenced as the process by which the software platform has been tested on very small components of models to ensure that inputs are appropriately replicated as outputs.

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 this 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:

1. Journey times on key routes and pedestrian flow counts taken at key locations should act as main elements for validation;

2. The simulated journey times of key routes should correspond with the surveyed journey times, and be within 10% of the latter; and
3. 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. In the following sections, model results are compared with observed metrics to present MM results within 10% of observed performance.

3.2. Validation scenarios

Table 2 describes the scale and populations of the four building egress case studies used for validation.

Table 2. Tower buildings used as case studies for validation of MassMotion.

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

3.2.1. Validation exercise #1: 155 Avenue of the Americas, New York

3.2.1.1. 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. A total of 232 employees were observed evacuating during the drill; 162 used Stairwell X and 70 used Stairwell Y. Video (to disseminate journey times, individual movements and behaviors) and manual counts (for occupancy and flow data) were collected.

3.2.1.2. 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 eliminated the pre-movement and detection times in order to focus on the total evacuation time.

$$t_{eva} = t_o + t_{pre} + t_{mov} \qquad (2)$$

Where t_{eva} is the total time for evacuation, t_o is the detection and notification time, t_{pre} is the pre-movement time including response and recognition time, and t_{mov} is the movement time including queuing time or travel time.

3.2.1.3. 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 3 shows the average of modeled journey times as compared with the observed travel times extracted from video.

Table 3. 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 overestimated 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 MM default agent stair speeds. The modeling team postulated 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 MM 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 MM 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.

3.2.1.4. 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 11^{th} 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.

Fig. 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.

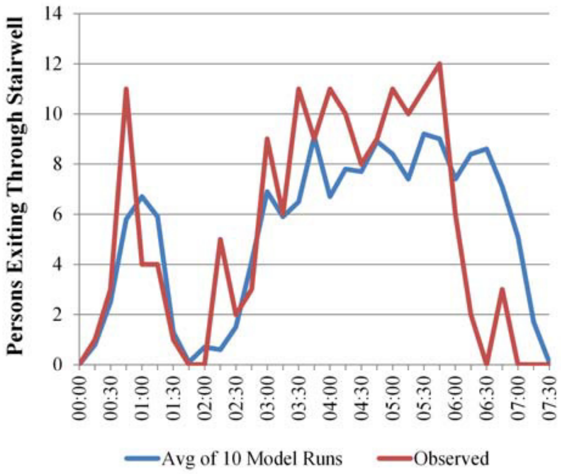

Fig. 1. Comparison of modeled and observed flow rates on the front stairwell exit.

Fig. 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 agents are generally slower to egress.

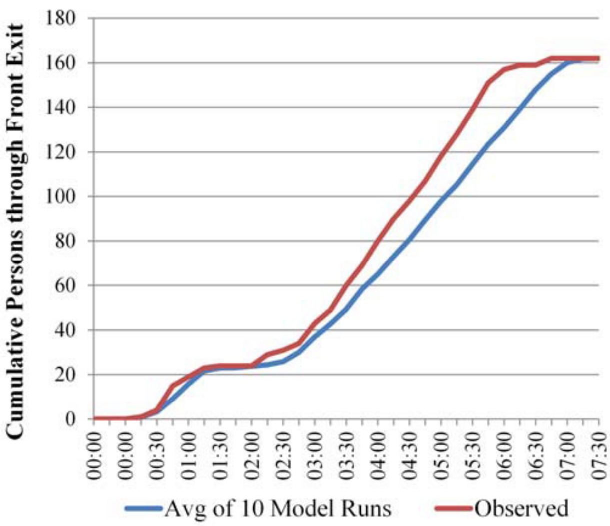

Fig. 2. Cumulative number of persons through front exit.

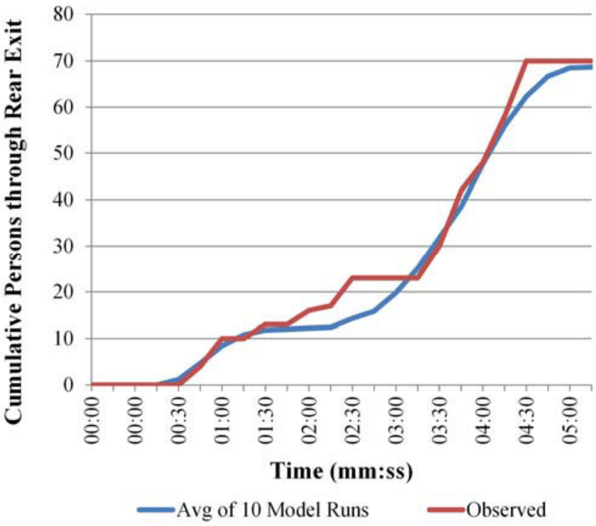

Fig. 3. Cumulative number of persons through rear exit.

Fig. 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.

3.2.1.5. Summary of validation exercise 1e: 155 Avenue of the Americas, New York

It is the opinion of the modeling team that the MM 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.

3.2.2. Validation exercise #2: 10 Hanover Square, NYC

3.2.2.1. Evacuation drill

The tenant of the office building at 10 Hanover Square, a 22-story mid-rise tower in New York City, conducted a full-building evacuation in May of 2002. The evacuation consisted of 1,130 people (approximately 35% of the full building occupant load) 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 and indicated even distribution among the two stairwells.

3.2.2.2. Model results: journey time

Randomly generated seeds were used to run ten models. Results of the ten models were averaged for final results reporting. The MM 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.

3.2.3. Validation exercise #3: 85 Broad Street, NYC

3.2.3.1. Evacuation drill

The tenant of the 85 Broad Street New York office building, a 30-story tower, conducted a full-building evacuation in June of 2002. The evacuation consisted of 1,385 people (approximately 22% of the full occupant load of 6,164) and concluded in approximately 18 minutes. Counts and observations were conducted on the first floor of the building during the evacuation drill. The model was calibrated to the observed stairwell distributions.

3.2.3.2. Model results: journey time

The MM 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.

3.2.4. Validation exercise #4: Canary Wharf, London

3.2.4.1. Evacuation drill

On 30 October 2001 at 11:00am, a full scale simultaneous evacuation exercise of One Canada Square, a 50-story tower in London, was completed using all stairs and elevators located within the building. A total of 5,469 occupants were involved with the exercise. 2,939 people used the four emergency egress stairs and 2,530 people used the 32 passenger elevators. 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. 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.

3.2.4.2. 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.

3.2.4.3. STEPS model comparison

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 building geometry with an occupant load of 2,939 occupants split evenly between floors. Walking speeds were set as fixed variables for the STEPS model

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.

4. 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 modeling of mid-rise and high-rise towers for egress scenarios. Test models produced total evacuation times that are within 1% to 10% of observed total egress times, as shown in Table 4. Additionally, agent movements and behaviors on egress stairs and through doors corresponded well to observations.

Table 4. Summary of results.

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

Individual journey times in the MM 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 MM can be used to test building egress and evacuation scenarios and make recommendations for safety preparedness improvements.

References

Fruin, J.J, 1971. Pedestrian Planning and Design. Elevator World, Inc. Mobile, Alabama.

Helbing, D., Molnár, P., 1995. Social force model for pedestrian dynamics II. Institute of Theoretical Physics, University of Stuttgart, Stuttgart, Germany.

IMO, 2007. MSC.1/Circ. 1238 Guidelines for Evacuation Analysis for New and Existing Passenger Ships. International Maritime Organization, London, UK

Kyte, M., Tian, Z., Mir, Z., Hammeedmansoor, Z., Kittelson, W., Vandehey, M., Robinson, B., Brilon, W., Bondzio, L., Wu, N., Troutbeck, R., 1996. Capacity and Level of Service at Unsignalized Intersections; Final Report, National Cooperative Highway Research Program Project 3-46.

London Underground, 2009. Station Modeling with Legion Best Practice Guide, Issue v2, July 2009.

MassMotion, http://www.oasys-software.com/products/engineering/massmotion.html, Assessed July 24, 2014

Oasys Software Limited, 2014. MassMotion 6-0 UserGuide, EnglandPeacock, R.D., Hoskins, B.L., and Kuligowski, E.D. 2010. Overall and Local Movement Speeds During Fire Drill Evacuations in Buildings up to 31 Stories. National Institute of Standards and Technology Technical Note 165.