The Use of Advanced Evacuation Modelling For Building Design

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ABSTRACT

Evacuation and human behaviour in emergency situations is one of the most important aspects when designing “safe” buildings. A thorough understanding of the building, its means of escape, the amount and types of occupants, its alarm and detection systems, etc, is essential to improving the overall occupant’s safety.

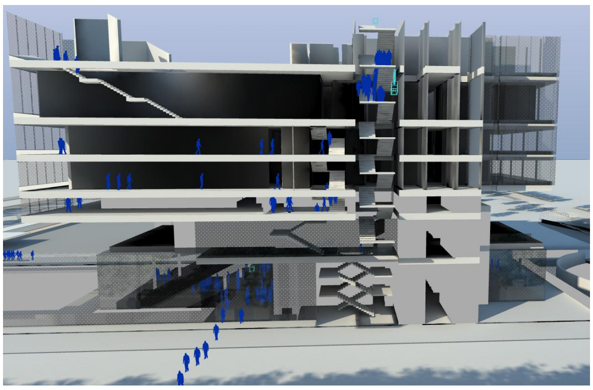
Although the means of escape for a building can be designed following prescriptive requirements, many examples exist where a performance based approach is more appropriate for complex buildings or buildings with large amounts of people, and where the use of advanced computer models is beneficial or even necessary to accomplish an intended design.

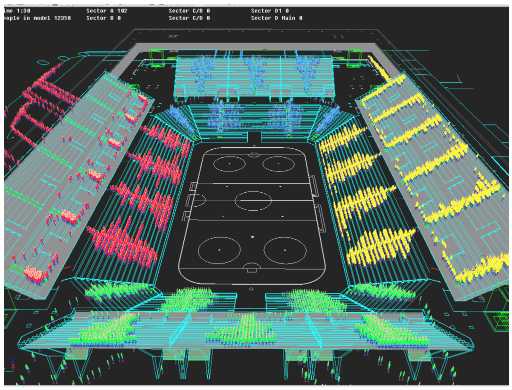
In the last two decades Arup Fire has used such models to evaluate, optimise and design the means of escape for large arenas, sport centres, high-rise buildings and other types of singular buildings.

The intention of this paper is to explain how advanced and productive evacuation modelling tools have developed and how they have been wisely used to improve the design of a few singular projects. The paper also identifies the important aspects to keep in mind when performing this kind of modelling. In particular, the paper shows how evacuation modelling was utilized in the following buildings:

- a 40 storey high-rise building,
- a large sports arena,
- a shopping centre containing existing heritage protected structures.

The computer models used to perform the analyses were STEPS, Legion and MassMotion.





1. INTRODUCTION

Evacuation modelling simulates human behaviour during emergency situations and is based on crowd dynamics and pedestrian movement within a defined geometry. Evacuation modelling can be applied to a wide array of building and infrastructure work.

In the past, the development of buildings has been based on prescriptive recommendations provided in various building regulations and codes. Current and future buildings are becoming more and more bespoke and the application of prescriptive recommendations is proving very restrictive to building designers. As a result of this, performance based design is now seen as a more appropriate method to allow building designers realise unconventional buildings.

The use of advanced evacuation modelling has become an integral part of the performance based design process to ensure buildings remain ‘safe’ for their occupants. While traditional hand calculations can be used for simple evacuation scenarios they are often not sufficient for complex designs. For such complex designs, advanced evacuation modelling can and has been used to:

- demonstrate and calculate overall building evacuation time,
- calculate queuing times and flow rates through exits and stairs,
- identify bottle necks along evacuation routes and,
- provide the overall design team and stake holders with an understanding of how the building operates in evacuation mode.

This paper explores various types of advanced modelling software packages such as Legion, STEPS and MassMotion and provides examples of where evacuation modelling has proven beneficial in the following buildings:

- a 40 storey high-rise building,
- a large sports arena,
- a shopping centre containing existing heritage protected structures.

2. 40 STOREY HIGH-RISE BUILDING

2.1 Project Description

The project consists of a new high rise tower that will be built in Turin (Italy). The architectural design foresees three stair cores from the top of the building to the 7th floor. From the 7th floor to the ground floor, the downward means of egress is reduced from three cores to two, forcing one of the stair egress flows to “merge” into the other two stairs via two “transfer corridors”.

The total occupancy of the building is significantly increased due to the presence of an auditorium located below the 7th floor. Hence, this special room requires additional egress measures to be implemented in the lowest floors. The estimated total number of occupants in the building is 5,600 people.

2.2 Modelling Program (LEGION)

The evacuation modelling was performed with the computer program LEGION. The software was developed through mass observations of crowd and evacuation behaviour from transport termini across several continents. This provides occupant profile data for resolving complex building, station and transport system design and management issues. Occupants are represented as learning-adaptive agents with individual preferences and objectives.

LEGION does not rely on a grid system to control the density and movement of entities. Instead LEGION uses a vector based system which places no artificial limitations on the geometry and allows realistic interactions between entities and their surroundings. This allows entities to move and interact with other entities in a realistic manner.

Some of the model's simulation capabilities include:

- simulating cross and counter-flows in normal operations,
- modelling merging flows in evacuation situations,
- predicting flow values and travel times in bottlenecks,
- mapping space utilisation, density and speed as a function of time with superior accuracy and granularity,
- modelling of arriving flows at more realistic estimates of size and shape of queues at congestion points.

The LEGION developers have validated the software against fire drill data and routine crowd egress from railway stations and major sporting events (Berrou, Beecham, Quaglia and Gerodimos, undated and referenced on http://www.legion.com/about-us/publications.php). Fire drills were undertaken with the cooperation of London Fire Brigade (http://www.legion.com/case-studies) of a multi-level office block in London.

Figure 1 below shows a 3D rendering of the entire building with references to some representative floors.

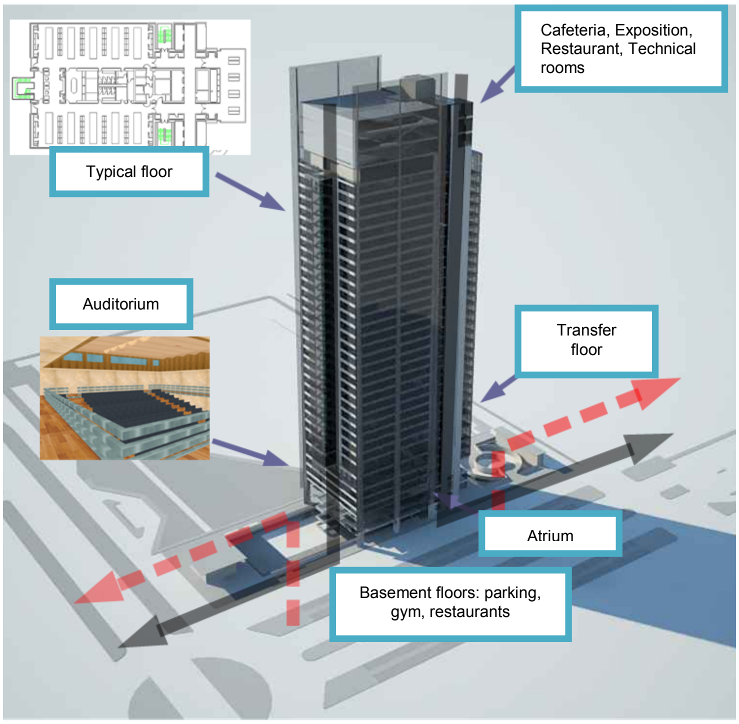


Figure 1: Building Rendering and Representative Floors

2.3 The Analysis

Different scenarios were modelled which were relevant during the design stages of the building.

The most important evacuation analyses undertaken were based on the following scenarios:

- Phased evacuation of the building considering a fire on the 10th floor.
- Simultaneous evacuation of the building considering a fire on the 10th floor.
- Simultaneous evacuation of the building considering a fire in the auditorium.

Figure 2 below illustrates specific moments during a modelled evacuation at relevant floor plans or critical locations of the building.

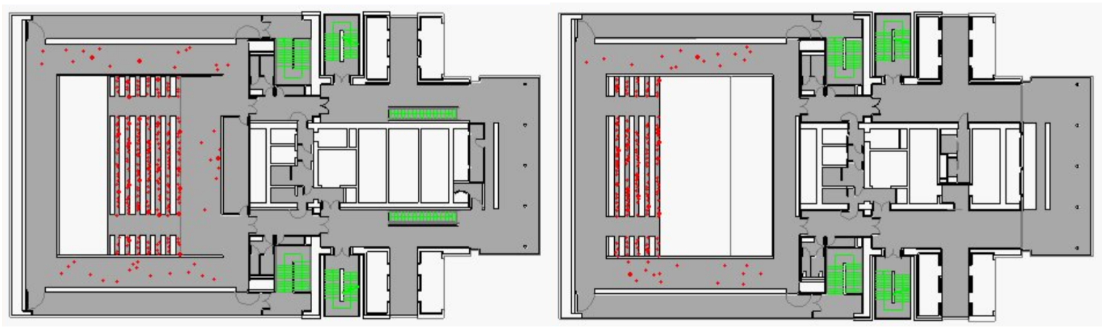


Figure 2: Evacuation of the Auditorium – At Time 0

Figure 2 above shows the auditorium located on the 7th and 8th floors of the building. The figure shows two floor plans, one for the occupants evacuating upward through an upper floor and the other for the occupants evacuating via a lower floor.

Figure 3 below shows different queues of auditorium occupants entering two different sets of stair cores. The cores are coloured green and the occupants are represented as red dots.

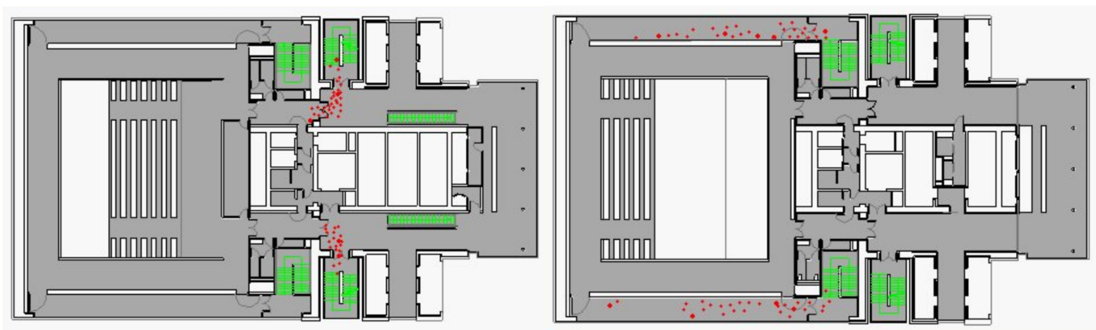


Figure 3: Evacuation of the Auditorium – At 1 Minute And 50 Seconds

In addition, a study of the auditorium itself was extrapolated and compared with a CFD analysis of the fire and smoke spread (to identify the ASET – Available Safe Egress Time). In particular, since the evacuation of the people was the main purpose of the analysis, all the output analysis was concentrated on temperature and visibility. These two factors were used to examine the impact of the fire and smoke on the occupants during the evacuation.

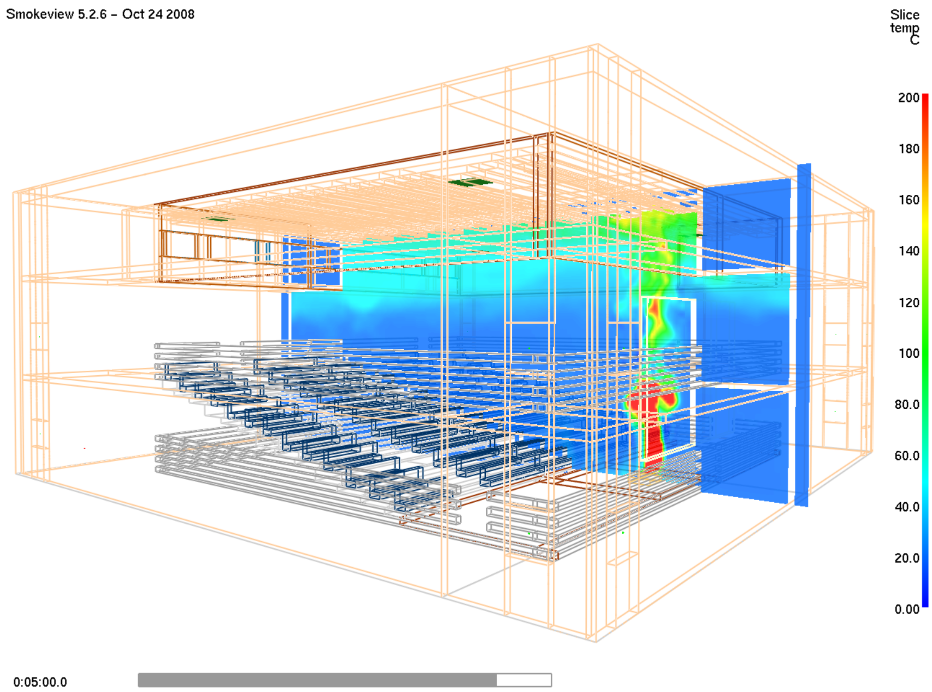


Figure 4: Smoke Modelling of the Auditorium

Figure 5 below shows the "transfer corridor" where occupants travel from one central core to two independent additional cores at the other side of the floor plan. Due to the large circulation area in the "transfer corridors", some queues with low densities are developed until they enter the stair core already occupied with other occupants and denser queues are formed.

Figure 5: Occupants flow through the "transfer corridors"

Figure 6 below shows a specific moment during the entire simultaneous evacuation of the high rise building, only the lowest floors are shown for better clarity.

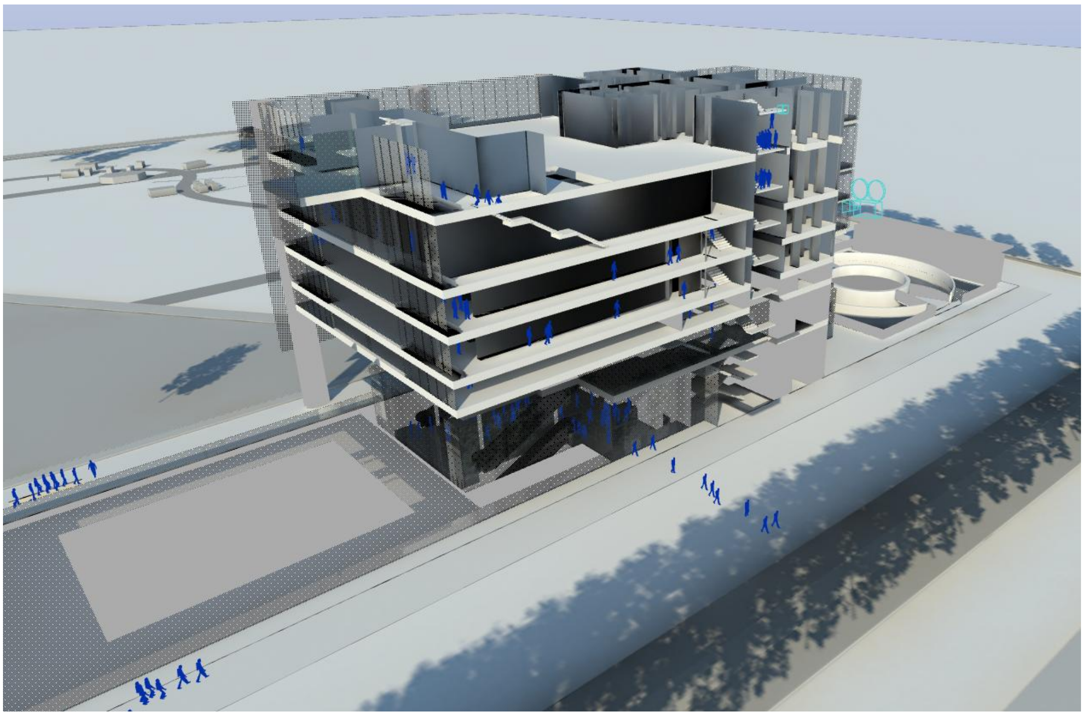


Figure 6: 3D Rendering of the Building during Evacuation

2.4 Results

The different models identified locations where the design needed to be further developed as some bottle necks in specific merging flows and in very crowded areas were present. The issues were resolved and the final design including a broken stair with two “transfer corridors” was justified as having safe egress means. For this specific project advanced evacuation modelling was a necessary tool that proved to be very useful.

The evacuation model proved the need to provide two independent stair cores for auditorium occupants so that they could quickly escape from the auditorium in the event of a fire, otherwise the occupants would be queuing for a longer period to enter the shared stairs serving other floors in a simultaneous evacuation of the building.

The egress model was also helpful to calculate an estimated evacuation time of the auditorium to later compare it with a calculated “Available Safe Egress Time”. The dimensioning of the egress means in specific crowded rooms like auditoriums can be clearly optimised with the help of advanced evacuation tools, while working in an integrated way with fire engineering strategies and the architects.

As the auditorium is just one part of the rest of the building, the model was also very valuable to investigate the differences and possible design variations when comparing a phased evacuation of the auditorium and the surrounding floors with a simultaneous evacuation of the entire building.

3. THE OLYMPIC ICE HOCKEY SITE

3.1 Project Description

The Palasport Olimpico is a multipurpose indoor sports/concert arena located at the Santa Rita district in Turin, Italy. With its 12,300 seats it is the largest indoor arena in Italy. Built for the 2006 Winter Olympics, it hosted, with Torino Esposizioni all ice hockey events. The building looks like a strict rectangular Cartesian coated stainless steel and glass box, with a footprint of 183m by 100m. The building consists of four levels, two underground (up to 7.5m below ground) and two above grade level (up to 12m high). The overall length of the plant is about 200m.

For the Winter Olympics game schedule, the following building use was foreseen: 2 games per day expected with a 2-hour turnaround time between games. This generally allows 15 minutes for people to leave the site and then a further 1 hour and 45 minutes to allow people to enter and be seated for the next game. Figure 7 and Figure 8 below show an internal 3D image and a section of the hockey area.

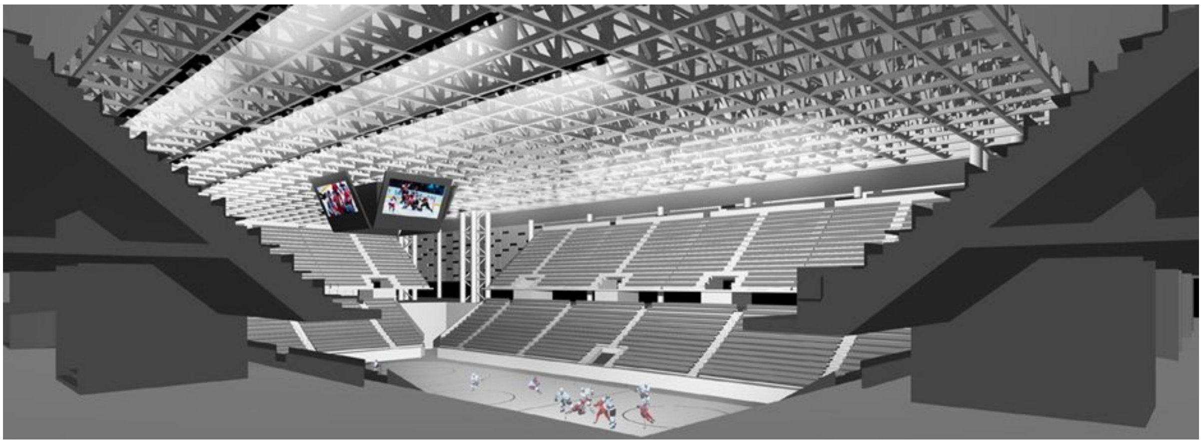


Figure 7: Internal Image of the Arena

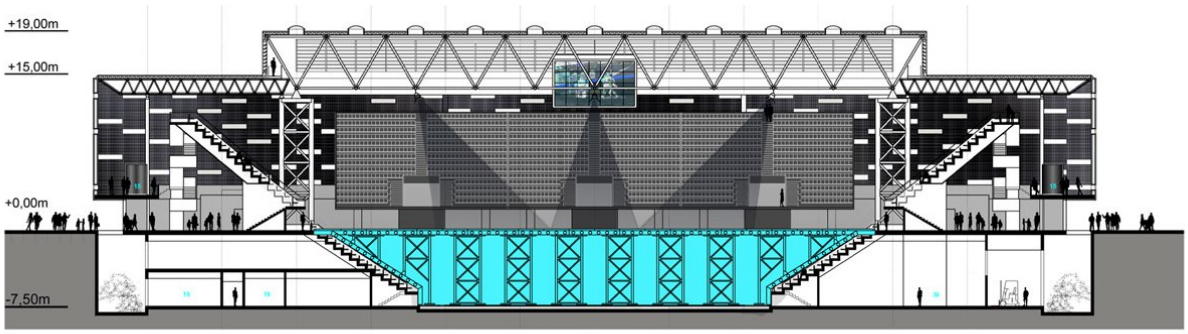


Figure 8: Section through the Arena

It was intended that the spectators could access the respective sectors of the building via the designated entrances provided. In addition to the main entrances, access to the upper level stands was provided via the stairs at either end of the stands.

However, for evacuation and end of game scenarios, the spectators of the upper level stands would be directed to leave the area via the five large vomitories provided without using the stairs. These vomitories discharge at ground level.

The intention was to control this crowd movement through the implementation of management procedures e.g. stadium staff standing at the upper vomitories and directing people not to use the route.

3.2 Modelling Program (STEPS)

The STEPS (Simulator of Transient Evacuation and Pedestrian movementS) is a computer programme that simulates the movement of people during normal and emergency evacuation scenarios in a wide variety of built environments.

STEPS uses advanced visualisation techniques to produce realistic, detailed real-time 3D simulations that are easily interpreted by designers, helping identify natural bottlenecks and preferred exits as well as testing evacuation routes and timings for different emergency scenarios.

It can model any environment, incorporating blockages or restrictions such as doorways, seating or kiosks.

STEPS can assign people with specific individual characteristics to account for factors such as age, gender, and familiarity with exit routes. It can also specify how individuals will react to their particular surroundings and with one another. Another unique feature is its ability to change conditions during evacuation in order to simulate events that may occur in real life.

STEPS is a grid-based evacuation model where every person is placed individually on the floor plans obtained from CAD-drawings. Floors can be linked together by stairs that the user defines within the program. Each individual is given a certain size and travel speed, which affect their movement. The ice hockey arena evacuation analysis carried out assumed a uniform population of equal size and travel speed.

The movement of people is based on a constant travel speed that is assigned to each person individually. The person will move with that speed as long as they are at a certain pre-set distance from any other person. If a person is within this distance they will not move until the distance is long enough for them to move again.

The population on each floor choose an escape route based on the shortest travel distance and/or less congested to a final exit, speed of movement on the route and their own impatience factor. An impatient person will not queue at the entrance to an exit for very long. They will go and find an alternative exit.

3.3 The Analysis (Initial Study with STEPS)

The evacuation assessment of the stadium required the evaluation of the viability of this procedure (normal ingress/egress) but also to look into how the emergency evacuation would work.

The following scenarios were initially carried out:

1. Scenario 1 – Simultaneous evacuation of the building using external sector barriers and then through the site boundaries.
2. Scenario 2 – Simultaneous evacuation of the building not using external sector barriers near Sector B and D and then through the site boundaries.
3. Scenario 3 – Simultaneous evacuation of the building considering the final exits at the building facades.

Scenario 3 was modelled to calculate the total time for people to actually leave the building and enter a “place of safety”.

3.4 Results (Initial Study with STEPS)

The scenario 1 model estimated the total evacuation of the building (excluding basements) using external sector barriers and then evacuating through the site boundaries. The total evacuation time for scenario 1 was 10 minutes and 57 seconds (10:57).

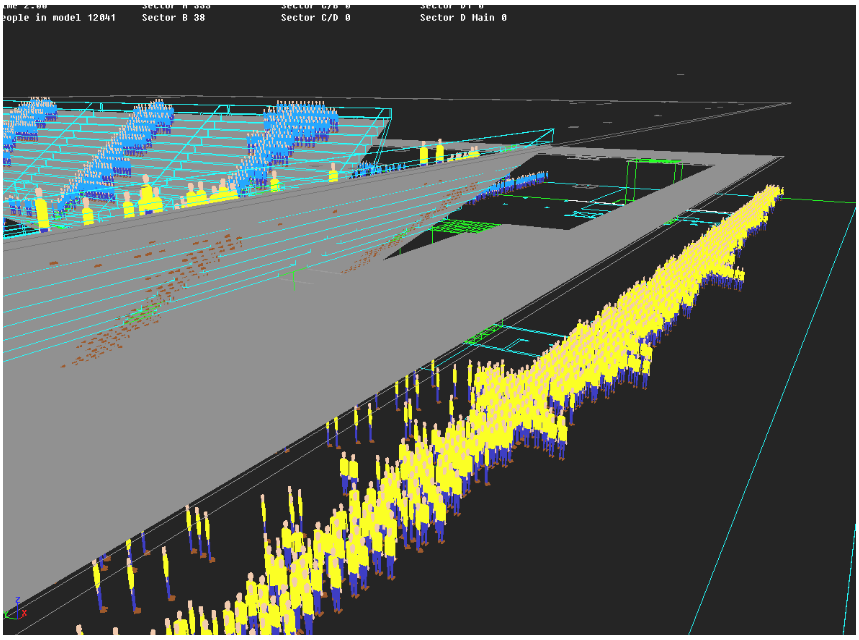


Figure 9: Sector D Main Exit

The model showed the occupants of sector D exiting down the side of the building towards the main boundary exit. The reason that they were adhering to the side of the building was due to the minimum distance based nature between occupants in the software and due to the constant travel speed of all occupants.

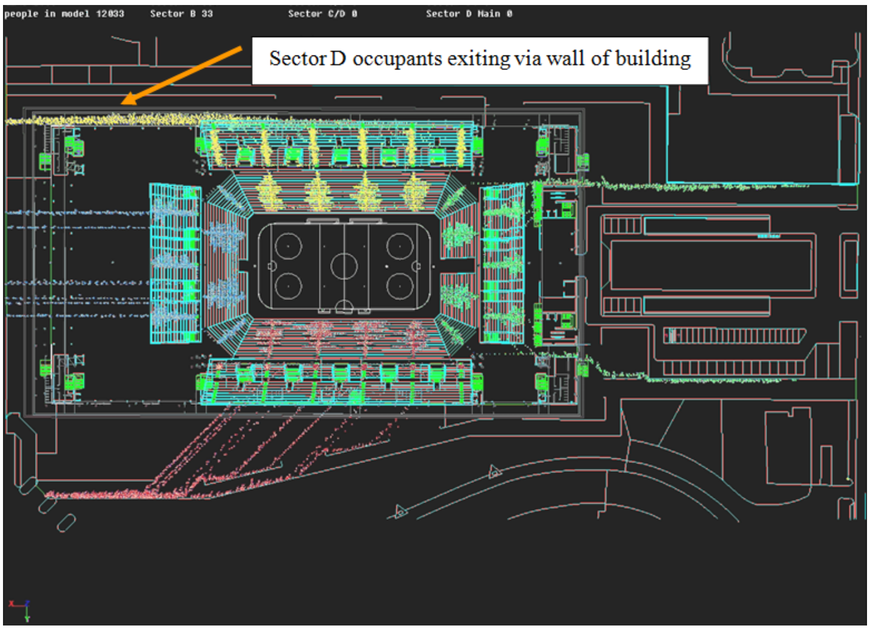


Figure 10: Sector D Occupants Exiting

3.5 The Analysis (Additional Study with LEGION)

In addition to the first evacuation study done with STEPS, an additional study was carried out 5 years later. The building owners indentified a need to diversify the use of the stadium and use the venue to host concerts and other non sport events. To enable this, the playing area was to be covered and used as a spectator viewing area during events. Hence, the new evacuation modelling considered the stadium occupants in the seating areas and also in the playing area.

The purpose of the modelling was to extend the original evacuation analysis by investigating the evacuation of the playing surface floor in "concert" configuration. This area could have a maximum allowable capacity of 3,000 spectators at any planned event. Therefore, this analysis was undertaken based on a maximum occupation of 3,000 people inside the playing surface.

The layout of the spectator stands remained as originally built and therefore as simulated in the previous modelling study.

The proposed egress routes from the lower seating areas were independent from the egress routes of the upper stands until the occupants reached the main circulation area at ground floor. At the circulation surface A1, the occupants from the lower seating areas interacted with the spectators from the upper stands and formed a unified evacuation. From the circulation area A1, occupants exited to the last circulation area A2 via signed exit doors. From there they could proceed to final exits.

Figure 11 below provides a detailed timescale of events during the evacuation of the modelled scenario.

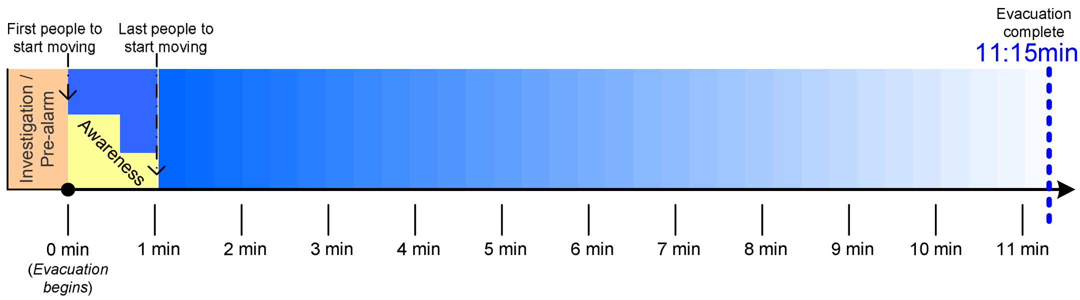


Figure 11: Timescale of Events

3.6 Results (Additional Study with LEGION)

Figure 12 below shows the maximum densities that were found in specific areas of the building throughout the evacuation at the lower stands and ground floor and the upper stands. These figures clearly show where congestion occurs. The maximum density values correspond to the red areas representing approximately 5 to 6 persons/m². These are areas where spectators need to queue for a relatively long period.

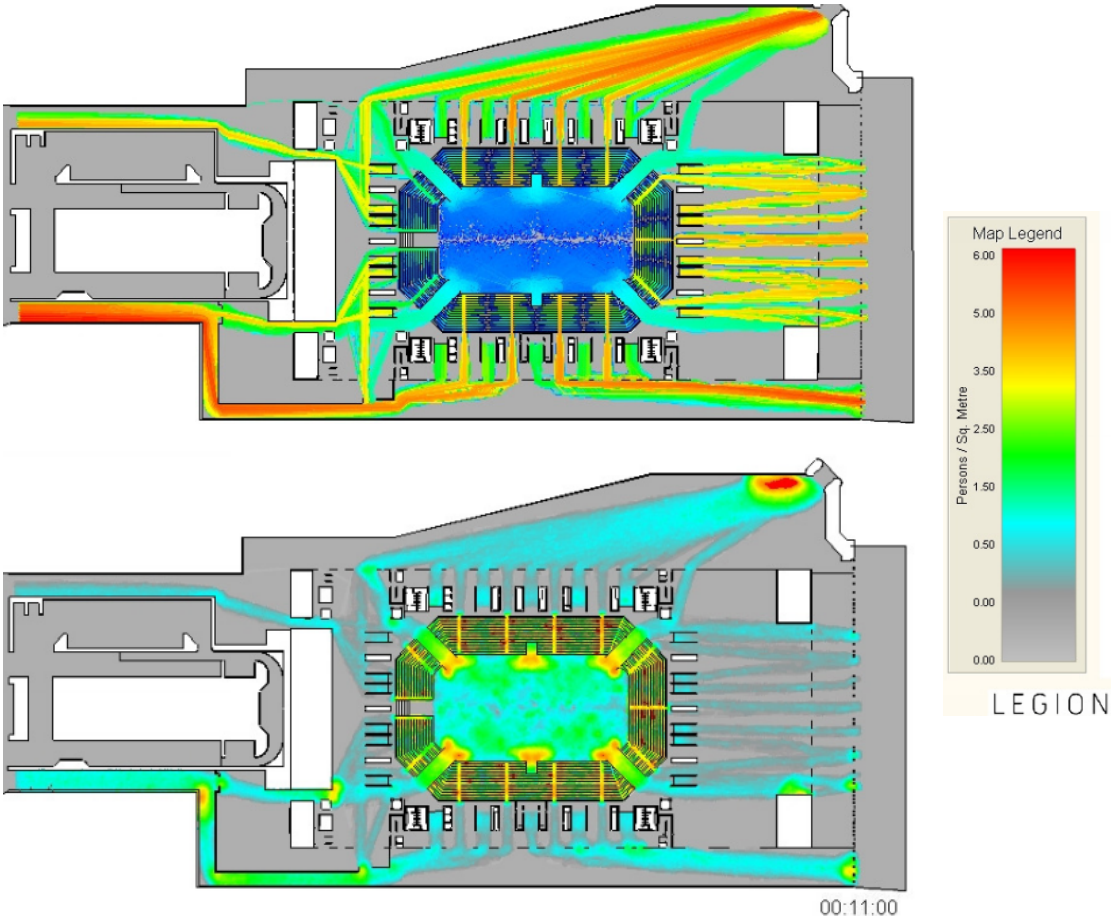


Figure 12: Maximum Densities at Ground Floor and Lower Levels

The evacuation modelling performed identified and subsequently allowed us to assess the following:

- The largest congested area is the north final exit. Some areas reached maximum densities of 5 persons/m². At this exit, the longest queuing time for any occupant during the evacuation is approximately 60 seconds.
- The radial aisle way exits of the lower stands have constant densities of approximately 3 persons/m² during most of the evacuation.
- The occupants of the playing field need to queue for a short period at the entrance of all exits where densities reach 4 to 5 persons/m².
- The south corridor leading to the southwest exits holds a smooth decent flow of evacuees with a density of approximately 2.5 persons/m² with a minor congestion at the last 90º bend.

The largest densities found along the evacuation routes were deemed acceptable as the occupants in these areas queue for short times and are close to the final exits.

The modelled scenario showed where the design needed to be further developed (bottle necks, narrow corridors, etc.) and for the final design it justified the stair core and evacuation concept for the building. For this specific project, advanced evacuation modelling was a necessary tool that proved to be very useful and that guaranteed a high level of reliability to the different stakeholders interested in the safety of the building.

4. MACDONAGH JUNCTION SHOPPING CENTRE, IRELAND

4.1 Project Description

MacDonagh Junction Shopping Centre is located in Kilkenny Ireland. The centre contains 36,000m² of car parking, 28,000m² of retail development, 3,000m² of commercial space, 135 residential units and a 122 bedroom hotel. At peak times the shopping centre can accommodate up to 8,000 people at any one time.

A number of heritage protected structures including an old railway terminus building dating back to the 19th century have been integrated into the modern shopping centre development. This required a sensitive approach and assessment to retain the existing features, structure and facade while refurbishing the building to achieve life safety requirements and the new uses.

Figure 13: Existing Retail Units within Shopping Centre

4.2 Modelling Program (MassMotion)

MassMotion is a 3D agent-based simulation tool, populated by individual, autonomous agents capable of making independent decisions in order to achieve a goal. Developed by Arup, MassMotion is founded on the construction of behavioural 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 behaviour profile. Agents have the ability to recognize congestion and will consider alternative routes based on their familiarity with the environment, adapting to current conditions.

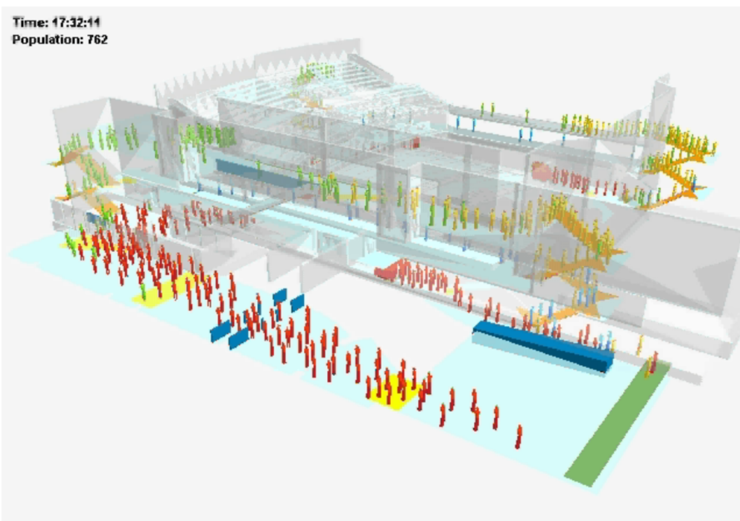


Figure 14: MassMotion Theatre Model

MassMotion can communicate complex problems in a highly visual manner and saves time, money and manpower during the planning phase of large projects. The program is fully 3-dimensional, built with gaming quality graphics and has the ability to program agents with individual personalities with unique agendas from start to finish in their journey through the environment. The visual and statistical outputs enable all stakeholders to engage in the design process regardless of their technical background. The application of MassMotion on various projects has led directly to design improvements and ensuring the most robust evacuation strategy is achieved.

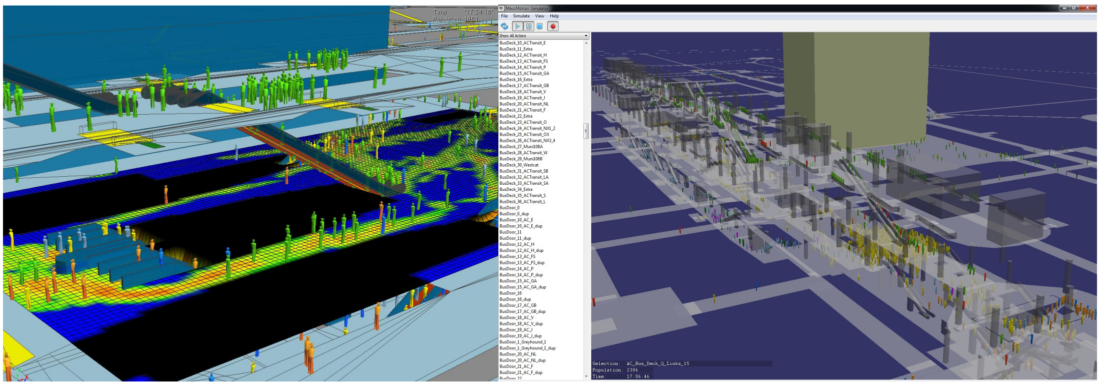


Figure 15: MassMotion - Transbay Terminal

Agent movements and decision making in MassMotion is done by dividing 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 neighbour 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 the equation below.

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

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

The 3D environment used in MassMotion can be constructed in Autodesk Softimage or imported from industry standard CAD and BIM tools. Agent behaviour 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 behaviour profiles. MassMotion provides outputs of critical statistics such as population counts, journey times, flow rates, and agent speeds.

4.3 The Analysis

Arup Fire provides ongoing fire engineering services to the shopping centre management team for this large shopping centre. As a majority of the buildings in the shopping centre are protected structures and therefore cannot be altered, advanced evacuation modelling has become an integral part of our service. MassMotion has been used to demonstrate that while code compliant means of escape is not always provided from the existing protected structures, sufficient means of escape to ensure the safe egress of occupants is available.

While a large amount of fire engineering and egress analysis has been carried out on the existing shopping centre a sample of where evacuation modelling has become particularly useful is outlined below.

One of the existing protected structures within the shopping centre has recently been fitted out. Compliant escape capacity was achieved however it was not possible to provide code compliant travel distances from the upper floors of the unit as this would mean altering the protected structure which was not possible.

MassMotion was used to demonstrate to the local approving authorities that when one exit was discounted due to fire the escape time from the unit was dictated by the compliant escape width rather than the non-compliant travel distance i.e. occupants will be queuing longer than the time taken to travel to the exit. To further demonstrate the robustness of the theory the speed of the occupant at the furthest travel point was set to an average of 0.675m/s to simulate a mobility impaired person (MIP).

4.4 Results

The use of MassMotion and evacuation modelling showed that the overall queuing time in the retail unit would be approximately 130 seconds and the time required for an MIP to travel an extended distance to the exit was 64 seconds. This demonstrated that the escape time for the MIP is dictated by the compliant escape width rather than the non-compliant travel distance. Therefore the extended travel distance in the unit does not pose and issue for an evacuating MIP.

Figure 16 below shows the position of the MIP at the furthest point of travel at the beginning of the simulation. Figure 17 below shows the location of the MIP at 50 seconds. It can be clearly seen that the MIP has reached the back of the queue of evacuating occupants and the extended travel distance does not affect the overall means of escape of the MIP.

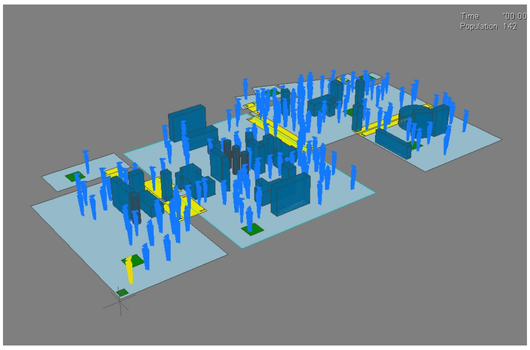


Figure 16 MIP @ 0 seconds

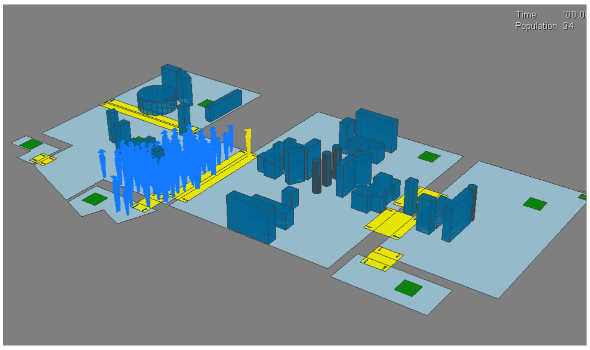


Figure 17 MIP @ 50 seconds

Figure 18 and Figure 19 show the corresponding crowd densities to the figures shown above.

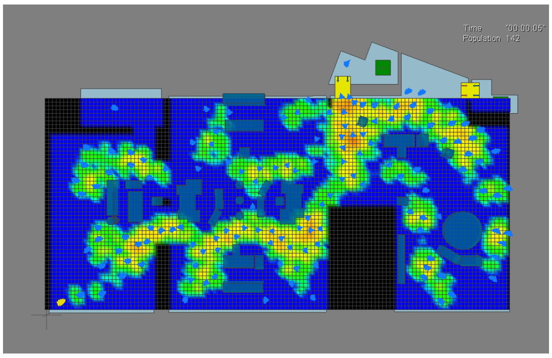


Figure 18 Crowd Density @ 0 seconds

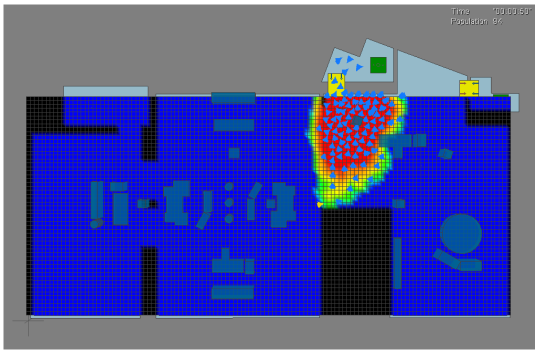


Figure 19 Crowd Density @ 50 seconds

- 3.3 m^2 per person or greater
- 2.3 m^2-3.3m^2 per person
- 1.4 m^2-23m^2 per person
- 0.93 m^2-1.4m^2 per person
- 0.46 m^2-0.93m^2 per person
- 0.46 m^2 per person or less

The use of software like this can be a particularly useful tool when presenting non code compliant designs to key stakeholders. This type of analysis allowed our client to have freedom in the design of the unit while working in the restrictive confines of a protected structure. The 3D visualisations from MassMotion as shown above ensured a relatively smooth process with a conservative local approving authority that are acutely aware of the needs of disabled occupants during fire evacuation scenarios.

5. CONCLUSIONS

This paper has presented three different examples of modelled buildings where evacuation flows were approximated and evacuation times estimated. Some of the output details have been shown with images and some explanations of results and benefits have been briefly explained with words. However, the benefits of evacuation modelling are countless and very diverse as they are beneficial to building developers, authorities, architects, fire safety engineers, building owners and the general public.

Some general benefits range from optimizing the economics of a building to be constructed, to improving the future use of old heritage buildings, to providing design flexibility for building designers, to providing safe premises for societies in general, etc. It is left to the reader to make good use of the design benefits explained in each of the three examples of this paper; some of these benefits may apply to other buildings, while other buildings could find similar benefits or find completely different ones. The intention of the authors is to point out that evacuation modelling programs have developed into powerful and helpful tools that provide flexible tools that can estimate realistic evacuation scenarios in a very practical way.

The paper also presents three different computer programs to clarify that many different software packages are available in the market and that they have been used in the past two decades on different projects. Many programs have been improved in the past years and new ones have emerged in recent years based on the experience of previous ones. Some of them are more practical at the time of building a model and others might be more helpful at the time of analysing the outputs. All models also have limitations and it is very important for the modeller to understand these for several reasons, however, the intention of this paper is not to compare the benefits and limitations of models but to show that modelling programmes have developed and that they have numerous capabilities to improve building designs.

6. REFERENCES

[1] Kuligowski and Peacock (2005). *'A Review of Building Evacuation Models'*. National Institute of Science and Technology, Technical Note 1471

[2] PD7974-6:2004. '*The application of fire safety engineering principles to fire safety design of buildings – Part 6: Human factors: Occupant evacuation, behaviour and condition (Sub-system 6)*'. British Standards Institution.

[3] S. Pheasant, *Bodyspace, Anthropometry, ergonomics and the Design of Work, Second edition.* 178-213 (1998).

[4] Evacuation modeling of Torino Ice Hockey Stadium, Winter Olympic 2006 Ice Hockey Stadium, 09/05/2003, Arup Fire

[5] Fruin, John J, (1971). *Pedestrian Planning and Design*. Elevator World, Inc. Mobile, Alabama.

[6] Helbing, Dirk and Molnár, Péter, (1995). *Social force model for pedestrian dynamics II*. Institute of Theoretical Physics, University of Stuttgart, Stuttgart, Germany.