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Journal of Fire Protection Engineering
22(3) 157–181

DOI: 10.1177/1042391512447044
jfe.sagepub.com

# Network modeling of The Station Nightclub fire evacuation

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**Abstract**
A network model has been used to study The Station Nightclub fire evacuation. Total evacuation times and occupant utilization of doors are compared to results obtained from previous work conducted at the National Institute of Standards and Technology and subsequent modeling carried out elsewhere. Depending on the selection of the door flow and exit choice algorithms the network model is able to get outcomes similar to those published by researchers using various fine grid/continuous models. New information regarding the occupant behavior during the incident has recently been published and this is used here to further investigate the capability of the network model.

**Keywords**
Evacuation, network modeling, nightclub fire, occupant behavior

## Introduction

The University of Canterbury has been developing a Monte-Carlo network occupant evacuation model (called EvacuatioNZ). As part of any model development there needs to be a continuous verification and validation process. Previous work has investigated the performance of the EvacuatioNZ model components [1], compared predictions with a trial evacuation [2] and examined the capability of the model to predict lecture theatre-type room clearance times [3].

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In this article, EvacuatioNZ is used to model evacuation scenarios that relate to The Station Nightclub fire, the ensuing investigation and subsequent modeling conducted by other researchers. Clearly one question that comes to mind is why is there any value modeling this particular event when a great deal of work has already been done? There are two primary reasons: firstly since a number of other models have been used to obtain predictions then this earlier work provides a benchmark for assessing the EvacuatioNZ model. In particular, these other models are all occupant-based fine network models and so it is useful to compare the course network approach used by EvacuatioNZ with these other tools. Secondly new information has recently been published by Fahy et al. [4] on the occupant conditions during the incident including the population profile, their familiarity with the building, their starting location at the time of ignition and the exits the occupants used. This new information can be used to revisit the evacuation modeling of the incident and further investigate the capability of the EvacuatioNZ model.

## Background

### *Incident description*

The Station Nightclub was a single-storey building in West Warwick, Rhode Island, USA originally built in 1946 but remodeled several times over its life. The fire occurred in February 2003 as a result of pyrotechnics igniting combustible foam material on the walls and ceiling surrounding the stage area at the start of a rock concert. The fire killed 100 people, of which 96 died inside the building, and injured at least 200 others. In addition to the effects of the fire, the evacuation was hampered by factors such as a certain level of unfamiliarity with the building, narrow doors and crowd crush. A considerable portion of the survivors escaped by breaking and climbing through windows and others were rescued by people from outside the building.

It is not the intention here to give a detailed description of the fire and evacuation that took place on the night. Grosshandler et al. [5,6] (hereafter referred to as the 'NIST' study) provide a comprehensive analysis of the fire development, people movement and emergency incident response. Their work also gives details of the subsequent scientific investigation into the cause of the fire, its development, the likely effect on the occupants, etc. Where appropriate, information such as the building geometry, occupant behavior and subsequent evacuation modeling are taken from the National Institute of Standards and Technology (NIST) study and additional information has been taken from the recent article published by Fahy et al. [4].

One important outcome of the NIST study was to show that, at around 90 s after ignition, the conditions within the main part of the nightclub were essentially untenable. This 90 s critical time point is used as part of the analysis in this article. However, it is noted that Galea et al. [7] suggest that computer modeling predicts flashover some 15 s earlier than in the actual fire.

## *Post-incident evacuation modeling*

NIST carried out a range of egress modeling investigations which considered three scenarios as part of their analysis of the incident. Under the first scenario (hereafter referred to as NIST Scenario #1), it was determined how long it would take to evacuate a building similar to The Station Nightclub with no fire present, assuming exit numbers, exit widths, and occupancy limits were consistent with the then current US model building codes. The other two scenarios examined situations in which doors became impassable at particular times. Due to the capability of the EvacuatioNZ model, the first scenario is of particular interest here, although the scenario for which the platform exit door is assumed to be blocked after 30 s but the front entrance is not (hereafter referred to as NIST Scenario #2*) is also investigated. NIST used two models for their investigation: buildingEXODUS and Simulex, which differ in their capabilities and their representation of geometry and occupants. It is not the intention here to go into detail about these models except that one obvious difference between the models used by NIST and EvacuatioNZ is that the former use a fine network/continuous representation of spaces. This means that the models used by NIST are able to identify the specific position of any occupant whereas this cannot be achieved in EvacuatioNZ because of its network representation.

Subsequent to the NIST modeling various other developers have used The Station Nightclub fire and the NIST modeling as a comparison with their own evacuation models. Again, the models and their application differ in many ways and only a brief summary is given here. Galea et al.'s [7] use of buildingEXODUS was much more involved than the NIST modeling as Galea et al. coupled modeling of the fire development, occupant toxic gas exposure along with an egress analysis. One of the outcomes of this work was that Galea et al. were able to compare the number and location of victims with the findings from the investigation along with the total evacuation times of survivors. The work by Pan [8] attempted to incorporate aspects of human psychology and sociology during emergencies into computational models for egress analysis and resulted in the development of a model called MASSEgress. Pan used this model to simulate The Station Nightclub evacuation, allowing for evacuation through windows depending on the 'stress' level assigned to the occupants. Chaturvedi et al. [9] created a dynamic data driven application system (DDDAS) to study the interaction between fire and occupant models during a fire evacuation. They compared DDDAS with the NIST modeling scenarios and declared DDDAS was able to give a good match for total clearance times. Unfortunately there is very little data available regarding occupant exit usage and other details. Finally the Pathfinder software [10] has been successfully compared with NIST Scenario #1 using three alternative occupant movement algorithms that are incorporated into the model. Similar to buildingEXODUS and Simulex, MASSEgress, DDDAS and Pathfinder all have the ability to track the specific position of occupants within the represented spaces.

**Table 1.** Distribution of the design and assumed actual occupant numbers used in the EvacuatioNZ modeling (zeros not shown for clarity)

| Room | Design occupant load | Fahy et al. (known) | Fahy et al. (unknown) | Victims | Assumed actual total occupant load |
|---|---|---|---|---|---|
| Dart room | 39 | 28 | 2 | | 30 |
| Sunroom | 76 | 16 | 1 | 59 | 76 |
| Dance floor | 237 | 185 | 12 | 41 | 238 |
| Main bar | 31 | 37 | 3 | | 40 |
| Entrance | | 17 | 1 | | 18 |
| Back platform | 18 | 15 | 1 | | 16 |
| Back hallway | 12 | 14 | 1 | | 15 |
| Stage | 4 | 21 | 1 | | 22 |
| Stage side | | | | | |
| Kitchen | 3 | | | | |
| Total | 420 | 333 | 22 | 100 | 455 |

## *Occupant numbers*

It is not clear exactly how many people were in The Station Nightclub at the time of the fire. According to the NIST study, the Providence Journal interviewed around 350 survivors. The NIST study quotes sources for the number of people which include one that claimed there were 458 occupants whereas Galea et al. [7] quote another source which reported 462 occupants. For reasons that are not clear (other than a misunderstanding between the number of survivors rather than the number of occupants), Pan [8] only used 350 occupants when modeling the evacuation using MASSEgress. Fahy et al. [4] estimated there were at least 455 on the night of the fire based on 355 witnesses interviewed by the police and the 100 victims. For the purposes of this article the total number of occupants is taken to be 455 to be consistent with Fahy et al.

The work conducted by NIST determined that the design occupant load for the nightclub would have been 420 people. These occupants would have been distributed around the building with the greatest density on the dance floor. This design occupant load was used by NIST in their evacuation modeling studies and is also used in this article when comparing with the NIST work. The exact number of occupants in each EvacuatioNZ node was determined by counting occupants in each space used in the NIST Simulex modeling.

Fahy et al. [4] determined the starting location of the 355 occupants they identified in their study and their data are summarized in Table 1. Fahy et al. were not able to assign starting locations for 22 people so here it is assumed that these

**Table 2.** Consolidated summary of exit used by location at ignition for survivors adapted from Fahy et al. [4] (zeros omitted for clarity)

| | Exit used | | | | | |
|---|---|---|---|---|---|---|
| Area at ignition | Sunroom window | Main bar door | Front door | Kitchen | Main bar window | Stage (Platform) |
| Unknown | 3 | | 10 | 1 | 2 | |
| Dart room | | 10 | 4 | 10 | 4 | |
| Sunroom | 8 | 1 | 4 | | 1 | 2 |
| Dance floor | 19 | 29 | 78 | 3 | 46 | 7 |
| Main bar | | 24 | 10 | | 3 | |
| Entrance | | | 17 | | | |
| Back platform | | 4 | 3 | 1 | 7 | |
| Back hallway | 2 | 3 | 3 | 3 | 2 | |
| Stage | 1 | | 4 | 1 | 1 | 14 |
| Total | 33 | 71 | 133 | 19 | 66 | 23 |

occupants were proportionally distributed in the same manner as those that were known. It is further assumed here that 100 victims were distributed between the dance floor and the sunroom such that the assumed occupant load effectively matched the NIST design occupant load (i.e. there are 238 occupants on the dance floor and 76 in the sunroom for both cases).

## *Exit usage*

During The Station Nightclub incident the use of exits by the occupants was likely driven by many factors including their familiarity with the building, their initial location when the fire occurred, the crowd congestion, the availability of exits due to the fire development etc. Clearly it is almost impossible to determine the exact decision making made by survivors let alone the victims. Fahy et al. [4] identified as best as possible how survivors managed to escape from the nightclub, whether that be through one of the doors or through the windows. Findings from Fahy et al. show that for the 240 survivors who specifically identified which exit door they used, 127 (53%) used the front entrance, 71 (30%) the main bar, 23 (10%) the platform and 19 (8%) through the kitchen. Fahy et al. found that around 101 of the 355 survivors (28%) escaped through the windows of the building and there were a small number of survivors for which the escape route was unknown. The NIST study reports that The Providence Journal found that of 169 people interviewed who escaped through a door, 91 (54%) used the front entrance which is equivalent to the 53% identified by Fahy et al. [4].

Fahy et al.'s analysis also related the survivor exit usage with their starting location and this information is used here for later comparison with the modeling.

**Table 3.** Summary of modeling results from selected NIST Scenarios. Percentages indicate proportion of agents using a given exit

| Equivalent NIST Scenario and egress model | | Total clearance time (s) | Front entrance door (ppl) | Platform exit door (ppl) | Kitchen exit door (ppl) | Main bar exit door (ppl) | Remaining in the building at 90 s (ppl) |
|---|---|---|---|---|---|---|---|
| #1 | Simulex [5] | 188 | 213 (51%) | 184 (44%) | 3 (1%) | 20 (5%) | 166 |
| #1 | building EXODUS [5] | 202 | 214 (51%) | 180 (43%) | 4 (1%) | 22 (5%) | 208 |
| #1 | MASS Egress [8] | 217 | 293 (70%) | 87 (21%) | 4 (1%) | 36 (9%) | 173 |
| #1 | DDDAS [9] | 226 | n/a | n/a | n/a | n/a | n/a |
| #1 | Pathfinder (SFPE) [10] | 235 | 207 (49%) | 191 (45%) | 3 (1%) | 19 (5%) | 153 |
| #1 | Pathfinder (SFPE+) [10] | 235 | 207 (49%) | 191 (45%) | 3 (1%) | 19 (5%) | 154 |
| #1 | Pathfinder (Steering) [10] | 214 | 201 (48%) | 197 (47%) | 3 (1%) | 19 (5%) | 183 |
| #2* | Simulex [5] | 308 | 356 (85%) | 39 (9%) | 3 (1%) | 22 (5%) | 256 |
| #2* | building EXODUS [5] | 341 | 364 (87%) | 32 (8%) | 4 (1%) | 20 (5%) | 274 |

n/a: not available.

These data are consolidated in Table 2 to correspond to the network modeling such that survivors on the ‘stage’ and ‘near the stage door’ are assigned to the ‘stage’; survivors ‘near stage or on dance floor’, ‘behind dance floor’, ‘between bars’ and ‘center stage-side’ are assigned to the ‘dance floor’; survivors using an ‘unspecified door’ are assigned to the ‘front door’; survivors using an ‘unspecified window’ are shared between the ‘sunroom window’ and the ‘main bar window’ and eight survivors whose exit was ‘unknown’ and the two given as ‘window or door left/right’ are omitted.

For the various evacuation modeling simulations it was relevant to determine how long it would be before the building was empty (i.e. the total clearance time) and which occupants exited by what doors. The results of NIST Scenario #1 and Scenario #2*, and subsequent modeling by others, yield the total clearance times shown in Table 3. In addition most of the modeling studies also reported the number of occupants that used the four available doors and the number that remained inside the building after 90 s of simulated evacuation, again shown in Table 3.

The NIST study noted that many survivors indicated that they were not aware of any exit doors other than the main front entrance. The report suggests that it could be argued that 2/3 of the people attempted (at least initially) to escape through the front entrance. Fahy et al. [4] suggest 60% of survivors had visited the club no more than ‘a few times’. Assuming this was the same proportion for the victims, then 273 of the 455 occupants could be presumed to be relatively unfamiliar with the nightclub. This 60% presumption is comparable to the 53% of those occupants who specifically identified which exit they used who exited through the front entrance door. If it is assumed that all of the 100 victims were unfamiliar with the building and hence the reason a large proportion were found near the front entrance then the percentage of people who used or attempted to use this door could have been up around 70%.

## *Pre-evacuation time*

In the incident there was some period of time before people reacted to the fire: not everyone would have responded at the same time due to their ability to see the fire, their sense of urgency, the behavior of people around them, etc. People’s reactions would have been different so that some attempted to leave the building almost immediately, others would have tried to find other members of their group whilst some waited to see what happened next. In several of the evacuation modeling studies the supposition was made that the occupants immediately responded to the fire and attempted to evacuate the building. The NIST study recognized that this assumption meant the modeling results gave shorter evacuation times than what would be expected even under a non-emergency evacuation.

Both the NIST study and Fahy et al. [4] describe a combination of qualitative and quantitative observations of the reaction of some of the nightclub occupants. From these observations it is possible to reasonably estimate the proportion of occupants who started to try to egress at a given time. In this article, the assumption is made that these observations are representative of everyone in the nightclub. A further assumption is made that the proportions are the same regardless of the initial location of the occupant. Clearly this assumption is unlikely to be wholly consistent with the actual event in which some people were on the dance floor and could clearly see the fire compared to those in more remote locations.

The NIST study states that a television camera operator, who happened to be filming on the night of the incident, began to evacuate 18 s after the fire started and he reacted before most people. At 24 s, the first occupants are seen to recognize the fire danger and by 30 s the bulk of the crowd had begun the evacuation process. The fire alarms sounded at 41 s after ignition. Fahy et al. [4] determined that of the people they identified 58 of them recognized that the fire was an immediate threat, 32 described the threat as ‘not good’, 8 heeded friends, 5 attempted to get fire extinguishers, 5 watched and waited, 80 thought that it was not bad and 3 stood

**Table 4.** Assumed pre-evacuation timeline based on Grosshandler et al.'s [5] and Fahy et al.'s [4] findings

| Time (s) | Number of occupants | Percentage of occupants | Associated comments |
|---|---|---|---|
| 18 | 1 | 1 | Reaction of the cameraman. |
| 24 | 58 | 30 | First occupants seen to recognize the fire danger/Those that recognized the immediate threat. |
| 30 | 120 | 63 | Time at which the bulk of occupants begin evacuation/Those occupants who considered conditions to be not good, not bad and heeded friends. |
| 41 | 13 | 7 | The activation of the fire alarms/People who tried to use extinguishers, those that watched and those 'in awe'. |

'in awe' of the fire. The descriptions indicate that some movement occurred by the occupants prior to their decision to head towards the exit so the term pre-evacuation time (referred to as response time by Galea et al. [7]) is used to indicate the time elapsed before movement towards an exit was attempted. From these descriptions the timeline shown in Table 4 was constructed to determine the pre-evacuation distribution. Clearly the timeline consists of some interpretation of the qualitative and quantitative observations but is considered at this stage satisfactory for the purposes of the EvacuatioNZ modeling.

## Network modeling

The modeling studies described in this article are split into two phases: the first phase compares the capability of EvacuatioNZ to replicate some of the evacuation modeling described by Grosshandler et al. [5] and others; the second phase employs the EvacuatioNZ model to examine the actual incident, particularly up until the 90 s critical time point.

### *Model description*

The EvacuatioNZ model uses a coarse network approach to represent a building to reduce computational times allowing for many repeat runs to be completed in a relatively short time. Building spaces are described by a network of nodes which are connected together by paths. Nodes are defined in terms of length and width dimensions and connections are defined in terms of their length and other characteristics. A network has to have one or more 'safe' nodes which represent final destinations for agents. Simulations are run over a defined time period or until all occupant agents have reached a 'safe' node. The simulation is broken into user-specified time steps typically of one second duration as is the case in this work.

People are represented as agents with their own behavioral and personal attributes. The model includes a range of exit behavior strategies including those that require the minimum travel distance to any 'safe' node, the minimum travel distance to a user-specified 'safe' node and those paths that are preferred by the agents. The choice of exit behavior can be probabilistically assigned to groups of agents. Pre-evacuation times can be represented through the use of distributions with the shape and statistics appropriately selected by the user.

Movement in crowded conditions is based on the equations provided by Gwynne and Rosenbaum [11] such that the relationship between speed of travel and occupant density is given by a linearly decreasing function for occupant densities greater than 0.5 ppl/m$^2$. Uncongested movement speeds can be fixed by the user or determined by the use of a distribution and a typical design value might be 1.20 m/s to correspond with Gwynne and Rosenbaum [11]. The model also accounts for the effect of queues at constrictions using the effective width concept [12] where a 0.15 m boundary is used for doors. The formation of a queue will depend on the presentation rate at the constriction and it is possible that no queue will form. An agent can only move through a constriction into a path if the occupant density in the downstream node is less than a maximum occupant density specified in the model. A maximum occupant density of 2.75 ppl/m$^2$ has been found to give suitable results in previous work [1].

The model has the ability to employ a range of distribution shapes whenever a statistical distribution can be specified for an input parameter and these distributions can be truncated at a specified upper and/or lower limit. Distributions can be in the form of a mathematical function or a user-defined frequency description.

The perceived advantages of a network model such as EvacuatioNZ are the ease with which simple building geometries can be created without the need for detailed CAD-like drawings or too much user effort and the relatively short computational time needed to run a simulation. For example, in this study ten evacuation simulations took around 8 s on a 2006 vintage 2.2 GHz single processor laptop. Geometrical input into EvacuatioNZ can be aided with the use of a third party graphical interface called yEd [13] (version 3.9) and there is also the capability to use this third party software to generate graphical output and simple animations. Version 2.3 of the EvacuatioNZ software is used in this article.

It is worth noting that in many cases the use of an evacuation model is mainly targeted toward the design of buildings rather than as a forensic tool. Models intended for design purposes are not developed to have the capability to reconstruct the exact timeline observed in an actual event at least not without some additional user intervention. This is certainly the case with the EvacuatioNZ model. For example the ability to close off an escape route as a result of the spread of fire or smoke is not available, nor is the ability to allow agents to escape through windows. Within a design context it would be virtually impossible to get a regulator to agree that escape through broken windows was a viable egress strategy so there is no benefit for the EvacuatioNZ developer to add such a capability.

## General set-up

The geometrical dimensions of The Station Nightclub are approximated as rectangular areas of equivalent size. Not every single space is individually represented in the network where those spaces were small and/or the number of occupants was likely to have been low. The distance between each node is specified by the center-to-center length. Constrictions are specified by their width; doors by the width reported in the NIST study and other openings (such as that between the dance floor and the main bar) from the drawing dimensions given by Grosshandler et al. [5]. The network geometry representation with respect to the building plan is shown in Figure 1(a). The steps and ramp outside the nightclub are not considered in the modeling similar to the NIST study. Although the steps may have slowed people movement they do not appear to have been a major factor during the incident. For some of the simulations a preferred route towards the front entrance is specified using the corresponding EvacuatioNZ functionality. These preferred routes are graphically shown in Figure 1(b) where the nodes have now been spaced further apart than in Figure 1(a) for clarity. Preferred routes only need to be defined between particular nodes as several nodes only have one connection anyway.

In all of the modeling, EvacuatioNZ is set-up so that agents start at a random distance from the first constriction toward which they move. Since occupants need to travel the center-to-center node length (L) before reaching their first constriction then the random distances are defined as $R = +/- \text{SQRT}(\text{node length}^2 + \text{node width}^2)$ so that starting distances are uniformly distribution with the limits $L + R$ and $L - R$.

## Baseline modeling

The starting point for the modeling is to deterministically use the geometrical network without the preferred routes, allow agents to select the minimum travel distance to any 'safe' node, use a fixed maximum unimpeded travel speed of 1.20 m/s, use the design occupant load of 420 agents distributed in the same manner as the NIST modeling, and assume there is no pre-evacuation time. The total clearance time from EvacuatioNZ is calculated as 493 s and this is significantly in excess of the 188 s obtained from Simulex and 202 s obtained from buildingEXODUS for NIST Scenario #1. The number of agents remaining in the building is 291 at 90 s compared with 166 agents in Simulex and 208 agents in buildingEXODUS.

Figure 2 shows the number of agents using the four available exits as a function of time. The use of the minimum distance algorithm has resulted in 347 agents (83%) using the platform exit door, 31 (7%) the main bar side exit door, 42 (10%) the kitchen exit door and none the front entrance door. This is quite different from the actual incident where most occupants used or appeared to try to use the front

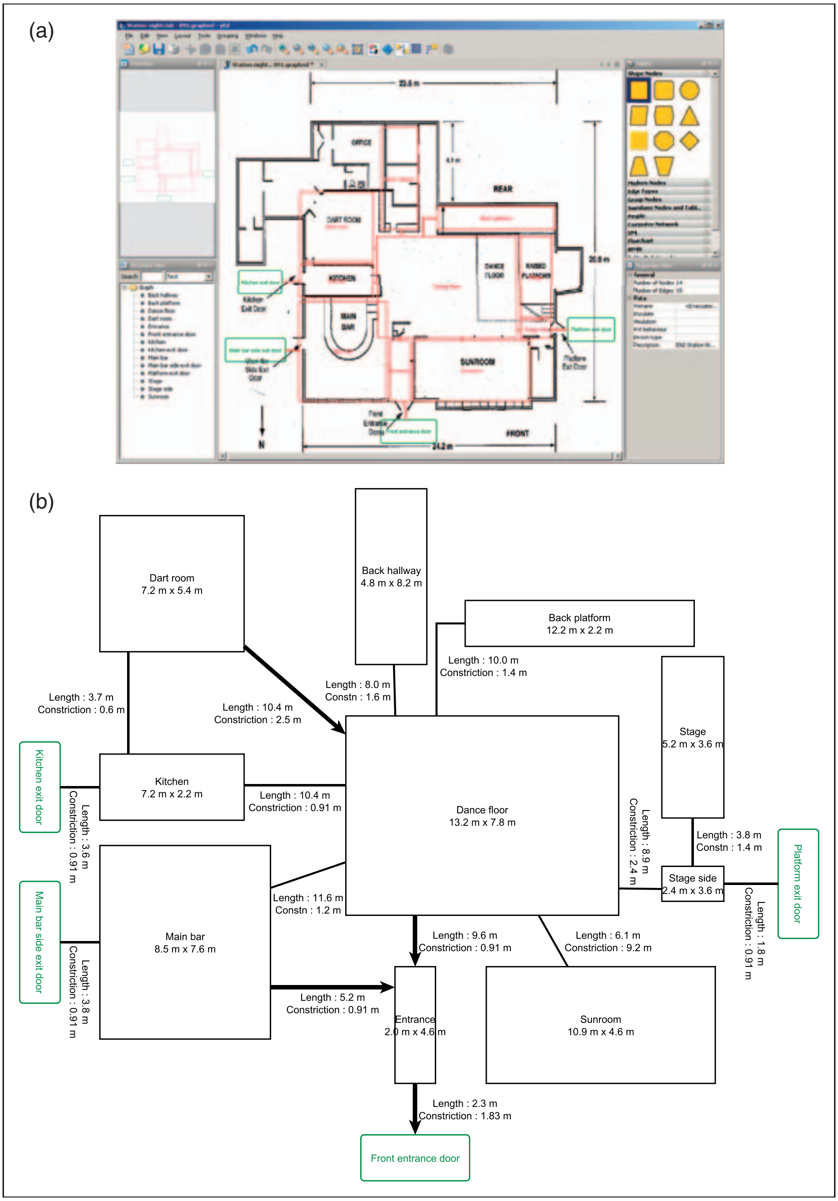


**Figure 1.** Network representation of The Station Nightclub used in the EvacuatioNZ model: (a) Using the yEd software to overlay the network on the building plan taken from Grosshandler et al. [5]; (b) Expanded network diagram showing node dimensions; connection lengths and constriction widths; and the preferred exit route indicated by bold arrows.

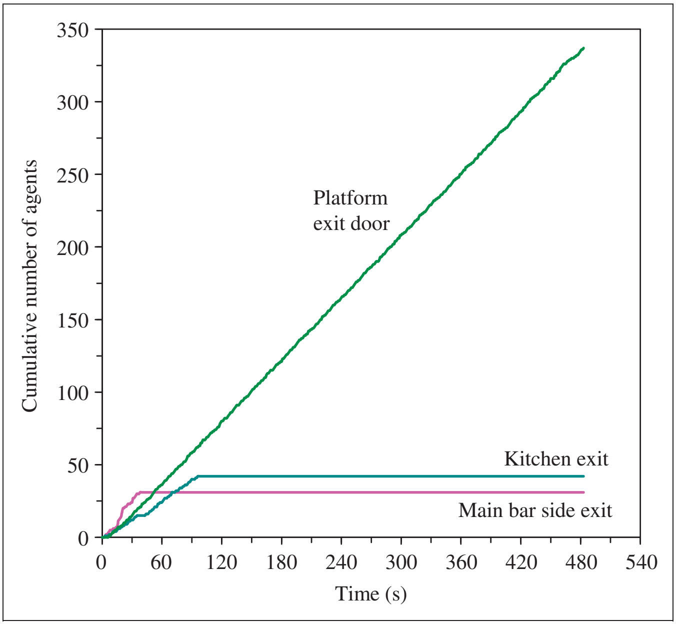


**Figure 2.** Number of agents reaching each exit node in the baseline EvacuatioNZ modeling.

entrance door and also quite different from the modeling conducted by NIST. On further investigation the EvacuatioNZ result is not surprising since agents that start or enter the dance floor node only need to travel 10.7 m to the platform exit door whereas they need to travel 11.9 m to reach the front entrance door. Unlike the fine node or continuous geometrical representations employed by buildingEXODUS and Simulex, the EvacuatioNZ node representation is unable to consider that an agent standing close to the entrance node only needs to travel a short distance when compared to the longer distance to the platform exit door. By making slightly different decisions regarding the distances between nodes it would be possible to have created a shorter path to the front entrance and so alter the outcome quite significantly; however, such adjustments are not made here as this would only serve to illustrate how a modeler could modify their input to simply obtain a desired result.

Distances specified for paths connecting nodes can have an effect on the performance of exit choice algorithms where distances are calculated by agents. The current default setup of the EvacuatioNZ model uses a 'minimum distance' algorithm so clearly the user has to carefully consider the implications of their representation of a building geometry in relation to the route finding algorithm/s they are planning to use. At this point it might simply be prudent to dismiss the network modeling as being 'incorrect' when the results differ so much from the other reported work but the modeling approach and results are worthy of further exploration.

## Door flows

The first item to consider is whether the total clearance time from EvacuatioNZ is comparable to what might be expected from a simple hand calculation. If the flow of 347 people through a 0.91 m wide door at an accepted specific flow of 1.33 ppl/s/m effective width [12] is computed then the actual flow, with a 0.15 m boundary each side, is 0.81 ppl/s so the total flow time is 428 s. This result is around 87% less than the EvacuatioNZ result of 493 s when the modeling also includes some additional travel time through the front entrance. When a similar calculation is carried out for 214 people (as given by the NIST buildingEXODUS modeling for Scenario #1) then a total time of 264 s is obtained and this is greater by around 25% than the 202 s given in Table 3. This raises the question as to why buildingEXODUS and the corresponding Simulex modeling result of 188 s are smaller than the hand calculation. Investigation of the NIST report shows that for the Scenario #1 code compliant analysis the 0.91 m wide doors are not reduced to a lesser effective width and a door flow of 1.21 ppl/s flow rate was applied in the buildingEXODUS modeling. If the 0.30 m boundary is ignored in the hand calculation then the flow also becomes 1.21 ppl/s and so the total time for 214 people is 177 s which more closely matches the NIST Simulex/buildingEXODUS modeling results.

The EvacuatioNZ model is therefore rerun with the same conditions as the baseline scenario but the width of all constrictions in the network increased by 0.30 m to effectively match the NIST modeling. The same exit usage as the baseline scenario occurs but now the total clearance time is reduced to 345 s. It is also noted that that after 30 s, 22 agents had used the platform exit compared to 39 agents in the Simulex modeling carried out by NIST and 23 survivors identified by Fahy et al. (Table 2).

Investigating the other published modeling results indicates that Pathfinder gave 191 agents through the 0.91 m wide platform exit door and a 235 s total clearance time (i.e. nominally 0.81 ppl/s) using its 'SFPE algorithm' assuming the last agent travelled through the platform exit door rather than the 1.83 m wide front entrance. Hand calculated values give 236 s at 0.81 ppl/s or 157 s at 1.21 ppl/s for 191 people through a 0.91 m wide door. In comparison, the MASSEgress model determined that 293 people had exited through the front entrance in 217 s which gives a nominal door flow of 1.35 ppl/s which is noticeably greater than the 1.21 ppl/s used in the NIST modeling.

## Matching exit usage

The results from not including the boundary layer are still in excess of the NIST modeling due to the 347 agents moving to the platform door exit. Thus, the next issue to investigate is how EvacuatioNZ compares with the other models if the same number of agents use each specified exit. The EvacuatioNZ model is setup so that specified agents moved to specified exits such that the total number of agents using each exit matches those in the NIST modeling in a way that tries to account

**Table 5.** Number of agents assigned to specific exit doors in the EvacuatioNZ modeling to correspond with the equivalent NIST Scenario #1 (zeros omitted for clarity)

| Room | To front entrance | To platform exit door | To kitchen exit door | To main barside exit door | Total |
|---|---|---|---|---|---|
| Dart room | 39 | | | | 39 |
| Sunroom | 38 | 38 | | | 76 |
| Dance floor | 118 | 119 | | | 237 |
| Main bar | 11 | | | 20 | 31 |
| Entrance | | | | | |
| Back platform | 6 | 12 | | | 18 |
| Back hallway | | 12 | | | 12 |
| Stage | | 4 | | | 4 |
| Kitchen | | | 3 | | 3 |
| Total | 212 | 185 | 3 | 20 | 420 |

for agents moving towards their closest exit. Having to force agents to use a specified exit has required some judgment on how many agents from each space travel to a given exit. The number of agents moving either towards the front entrance or platform door are evenly split on the dance floor and sunroom. Thereafter the exit selection of agents in the main bar and the back platform is defined such that the desired totals using each exit is achieved (Table 5).

The EvacuatioNZ simulation gives a total clearance time of 195 s and the total number of agents who have left the nightclub as a function of time essentially matches that obtained in the NIST modeling (Figure 3). If the boundary layer reduction is included in the EvacuatioNZ modeling then total clearance times are $272 \pm 2$ s compared to a hand calculated value of 261 s for 212 agents to flow through a 0.91 m wide door.

Hence, although the EvacuatioNZ model makes a number of simplifications with regard to the geometry of the building and the representation of agents moving through the spaces, the overall result is comparable to the fine network/continuous models if the number of agents using each exit is the same and no boundary layer reduction is included. One obvious criticism of this comparison is that the EvacuatioNZ modeling is only meaningful because the number of agents using the exits had already been determined by earlier modeling and so this point is addressed in the next section.

## *Preferred exit modeling*

As discussed in the 'Introduction' section it might be inferred that around 60% of the people in the nightclub were likely to be unfamiliar with the building and might have elected to try to escape through the front entrance as their first choice.

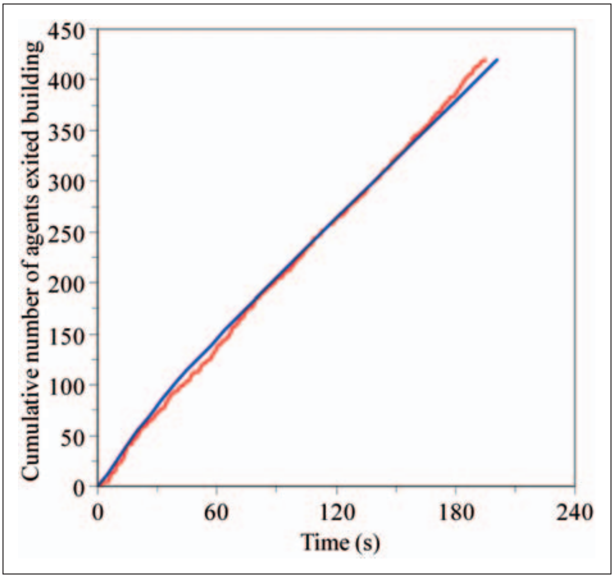


**Figure 3.** Comparison of the NIST Scenario #1 modeling for the number of agents who have exited the building with the EvacuatioNZ modeling where the number of agents using each exit has been explicitly specified.

The EvacuatioNZ preferred exit geometry configuration shown in Figure 1(b) is used to examine how a preferred exit selection affects the results. All of the 420 agents are assigned a 60% probability of following the preferred exit path or a 40% probability of using the minimum distance to any 'safe' node (i.e. the behavior used in the baseline modeling).Since probability values are assigned to the exit behavior then it is expected that a range of total clearance times will be calculated by EvacuatioNZ. Simulations are continued until the change in total clearance times is at or below an arbitrary convergence limit of 0.0005%, similar to previous work [3]. This same convergence limit is applied to each of the subsequent EvacuatioNZ modeling scenarios discussed hereafter.

Results for 428 simulations give a mean and standard deviation total clearance time of $201 \pm 8$ s and the minimum, average and maximum cumulative number of agents who have left the building per unit time is shown in Figure 4. The average total clearance time differs by 1 s when compared with the NIST results using buildingEXODUS (Table 3) although a greater proportion of agents have managed to exit the building during the middle phase of the simulation. Of the 420 agents in the EvacuatioNZ scenario, typically $67 \pm 3\%$ use the front entrance door, $3 \pm 2\%$ the main bar side exit door, $23 \pm 3\%$ the platform exit door and $6 \pm 2\%$ through the kitchen door. The number of agents remaining in the building after 90 s is around 163 compared to the 166 agents obtained in NIST Scenario #1 using Simulex.

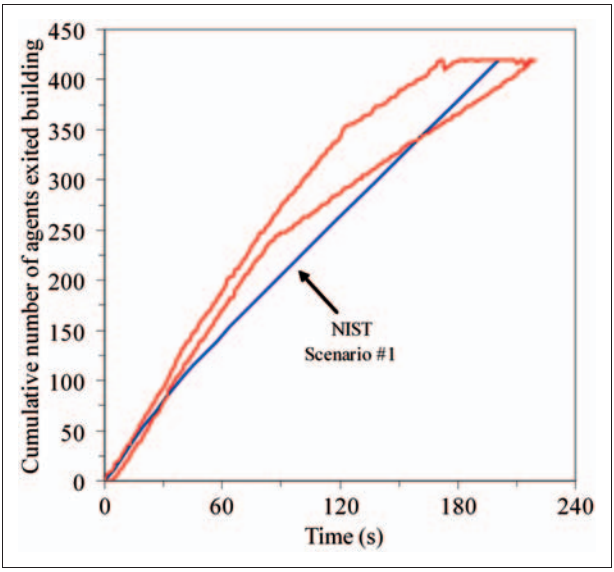


**Figure 4.** Comparison of the NIST Scenario #1 modeling with the minimum and maximum cumulative number of agents who have left the building from the EvacuatioNZ modeling, using the preferred exit routes.

Following on from the above discussion, it is now possible to recreate NIST Scenario #2* using EvacuatioNZ. The probabilities for agent route selection for the front entrance and platform are adjusted so that on average 22 agents exit through the platform exit door after 30 s similar to that obtained when recreating NIST Scenario #1. To get this desired number of agents, of the 397 agents that select the platform exit door or the front entrance door (Table 5) only 5.5% will now opt for the platform exit door. This approach is similar to that employed by NIST for their Simulex modeling in which the number of people allowed to use the platform was limited to the number determined by examining their Scenario #1 results.

The results from 81 runs of EvacuatioNZ give an average total clearance of $326 \pm 4$ s. Figure 5 compares the minimum and maximum cumulative number of agents who have left the building with the equivalent NIST Scenario #2* results. The number of agents remaining in the building at 90 s in the NIST study is 256 agents using Simulex and 274 agents using buildingEXODUS in comparison to around 246 to 271 from EvacuatioNZ. The comparison between EvacuatioNZ and the NIST modeling is similar in terms of the total clearance time and the number of remaining agents. Given these results, there can be some confidence that EvacuatioNZ is doing a reasonable job of modeling the NIST scenarios.

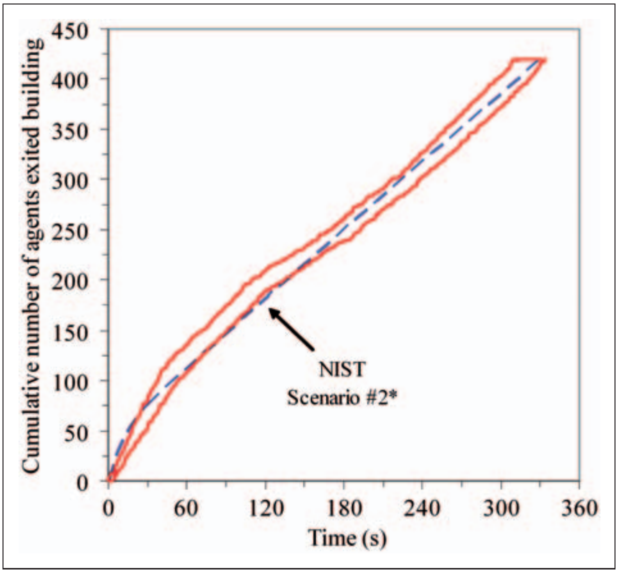


**Figure 5.** Comparison between the NIST Scenario #2* results (dashed line) with the minimum and maximum cumulative number of agents who have left the building from the equivalent EvacuatioNZ modeling.

## *Modeling evacuation of The Station Nightclub*

Even if there existed the 'perfect' model that captured all of the physical and behavioral complexities of an evacuation it would still be impossible to exactly recreate an incident as there would be uncertainties regarding the exact starting location of each individual, the decisions made by occupants at any instant in time, etc. Inevitably, modeling The Station Nightclub incident with a tool such as EvacuatioNZ can only be an approximation of what could have happened since, along with the limitations of the evacuation modeling, the model does not try to consider the effects of the fire. However, results from EvacuatioNZ, particularly up until 90 s, provide a useful comparison with the other work identified in this article. Readers are directed towards Galea et al. [7] to get a much better understanding of the complexity of trying to completely model an incident such as The Station Nightclub fire.

In the current study, modeling The Station Nightclub incident uses the estimated actual occupant load distributed as shown in Table 1 and the pre-evacuation distribution discussed earlier in Table 4. Agents are assigned ages and sexes using the population profile of survivors given by Fahy et al. [4]. Similar to previous work [3], a functional relationship between sex, age and walking speed using Ando et al.'s data (as cited by Smith [14]) is taken as the starting point. Ando et al.'s data does


**Figure 6.** Comparison of walking speed as a function of sex and age from an adaptation of Ando et al. with mean, maximum and minimum range values (dashed lines) from Lord et al. [15].

not include any variability in the walking speed so the distributions for speed at a given age by Lord et al. [15] were applied to the Ando et al. data (Figure 6). It is recognized that the Lord et al. data are only specified for three broad age bands and mean values somewhat differ from Ando et al. but are sufficient to give maximum and minimum limits for free walking speeds.

So as to match Proulx [12], the boundary layer reduction has been applied to specific flows through constrictions. Similar to the previous modeling, all of the 455 agents are assigned a 60% probability of following the preferred exit path or a 40% probability of using the minimum distance to any 'safe' node. As a result, the mean and standard deviation total clearance time is $324 \pm 14$ s and Figure 7 shows the minimum and maximum cumulative number of agents that have exited the building using EvacuatioNZ. In Figure 7, the NIST curves have been linearly extrapolated to give total clearance times for 455 agents. The overall shape of the EvacuatioNZ curve predominantly falls in-between the two NIST Scenarios (i.e. NIST Scenario #1 and NIST Scenario #2*) and, as would be expected, there is a delay before agents start to leave the building due to the pre-evacuation distribution.

The total clearance time from the modeling has little relevance to the incident but the results up to 90 s provide a useful comparison with Fahey et al.'s findings. Figure 8 shows automatically generated snapshots from the EvacuatioNZ modeling at 0 s and 90 s using the yEd software. The number and total percentage of agents are shown for each node and darker shading shows where the higher occupant densities occur.

Results from EvacuatioNZ show $172 \pm 4$ agents have exited the building after 90 s. If it is assumed that people during the incident were only able to use the doors up until the first 90 s, then Table 6 compares the percentage of survivors reported

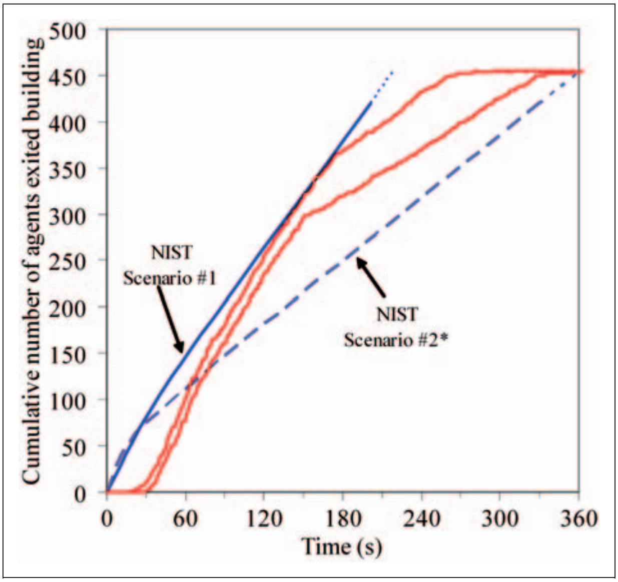


**Figure 7.** Cumulative number of agents that have exited the building for the EvacuatioNZ modeling of The Station Nightclub incident compared with linearly extrapolated NIST Scenario#1 and NIST Scenario #2* results.

by Fahy et al. [4] who used a door to escape (when their starting location was known) with the EvacuatioNZ predictions. Fahy et al. found that there was a wide dispersion of people starting at different locations who were able to use the doors (albeit comparatively small percentages) whereas EvacuatioNZ only has agents who have started in a much narrower range of nodes using a door. Compared to Fahy et al. [4], EvacuatioNZ under-predicts the percentage of people using the front entrance by around 4.0 percentage points but under-predicts the percentage using the main bar side door by more than half and the percentage using the platform exit door by about three times the amount. However, it is also useful to compare the total predicted percentage of agents that exit from each starting room with the incident data. The number of agents who exit through the front entrance after 90 s is between 86 and 95 compared to the 133 identified by Fahy et al., so it would be interesting to know what proportion of survivors managed to escape after 90 s. Grosshandler et al. [5] state that the front entrance was clogged in less than 100 s.

At the 90 s critical time there are still on average 283 agents in the building using EvacuatioNZ. If it were assumed that the approximately 101 people noted by Fahy et al. were able to escape through windows, then the EvacuatioNZ modeling 'predicts' (using the term quite loosely) 182 fatalities. Galea et al. [7] obtained 180 fatalities from their simulations, which was reduced to 84 when a delay of 15 s was introduced into the development of the fire to compensate for the faster

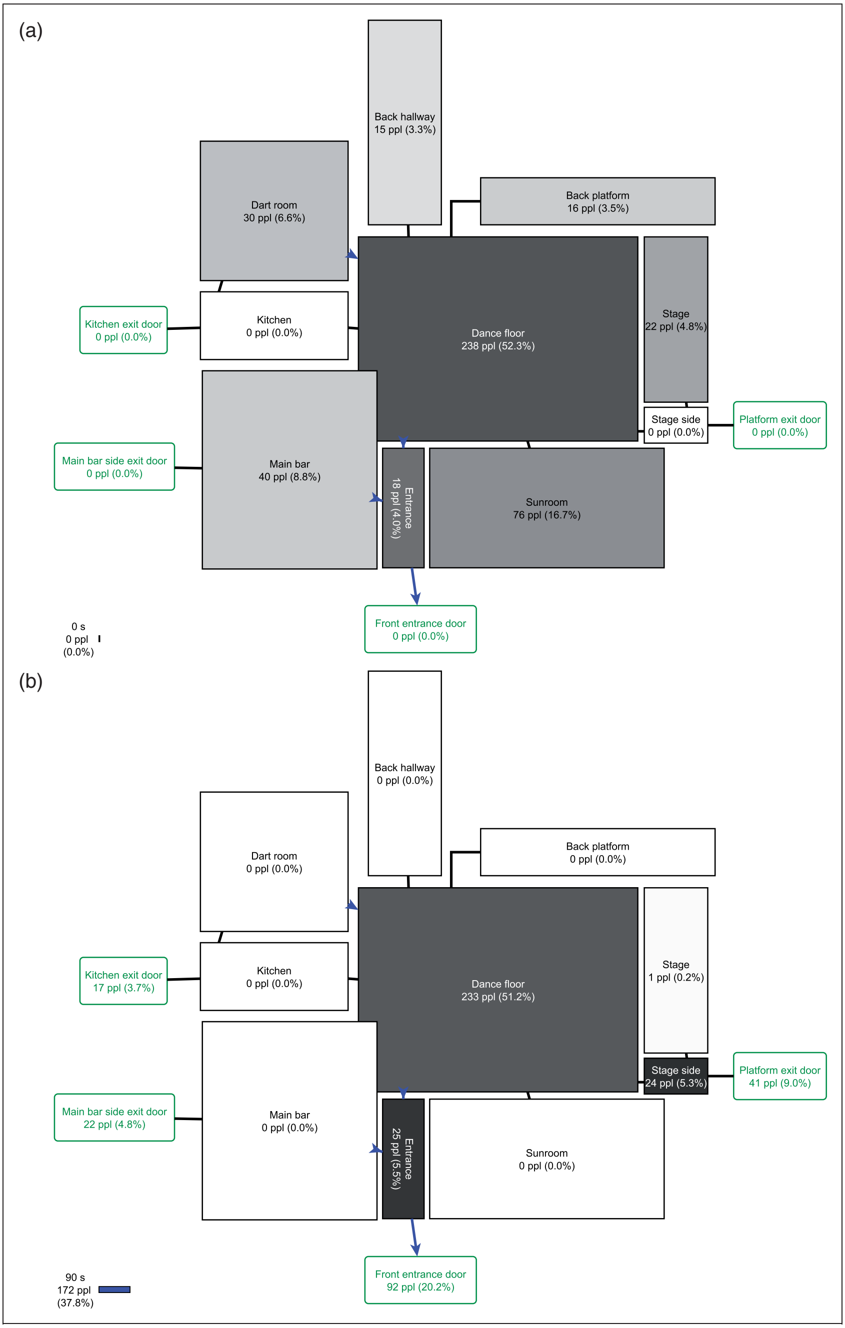


**Figure 8.** Snapshots of the EvacuatioNZ modeling at (a) 0 s and (b) 90 s. The number and total percentage of agents are shown for each node and darker shading shows higher occupant densities (some node labels have been recolored for readability).

**Table 6.** Approximate percentage of survivors reported by Fahy et al. [4] who used a door to escape, when their starting location was known, compared with the EvacuatioNZ predictions (shown in parentheses) at 90s (zero values omitted for clarity)

| | | Door exit used | | | | |
|---|---|---|---|---|---|---|
| | | Main bar side | Front entrance | Kitchen | Platform | Total |
| Starting room | Unknown | | 4.1% | 0.4% | | 4.5% |
| | Dart room | 4.1% | 1.6% | 4.1% (12.4%) | | 9.8% (12.9%) |
| | Sunroom | 0.4 % | 1.6% (0.6%) | | 0.8% | 2.8% (0.6%) |
| | Dance floor | 11.8% | 31.7% (30.9%) | 1.2% | 2.8% (12.9%) | 47.6% (43.8%) |
| | Main bar | 9.8% (13.5 %) | 4.1% (8.4%) | | | 13.8% (21.9%) |
| | Entrance | | 6.9% (10.1%) | | | 6.9% (10.1%) |
| | Back platform | 1.6% | 1.2% | 0.4 % | | 3.2% |
| | Back hallway | 1.2% | 1.2% | 1.2% | | 3.6% |
| | Stage | | 1.6% | 0.4 % | 5.7% (11.2 %) | 7.7% (11.2%) |
| | Total | 28.9% (13.5%) | 54.1% (50.0%) | 7.7% (12.4%) | 9.3% (24.2%) | |

predicted flashover. If the number of agents in the building after 105 s is considered (to correspond with Galea et al.'s suggestion regarding the actual time to flashover) then only another 37 or so agents have escaped, giving around 145 fatalities. This compares to the 100 fatalities that occurred during the incident, but it would be inappropriate to claim this is a meaningful prediction using EvacuatioNZ. It is noted that Pan's MASSEgress modeling obtained 89 fatalities, although this result should be treated with care given the significant underestimate of the number of people in the building and the fact that Pan used 300 s after ignition as the critical point to determine the number of people who had managed to safely escape.

EvacuatioNZ is also applied to match NIST Scenario #2* in which, of all agents that select the platform exit door or the front entrance door, only 5.5% will opt for the platform exit door. As a result the mean and standard deviation total clearance time is $494 \pm 9$ s and Figure 9 shows results in the same form as Figure 7. As might be expected, EvacuatioNZ simulations now give longer total clearance times when compared to the equivalent NIST Scenario #2* results since the boundary width

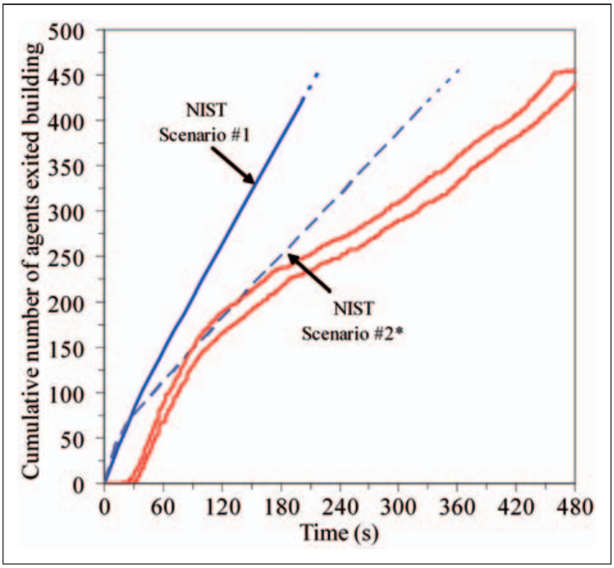


**Figure 9.** Cumulative number of agents that have exited the building for the EvacuatioNZ modeling of The Station Nightclub incident with restricted use of the platform exit door compared with linearly extrapolated NIST Scenario #1 and NIST Scenario #2* results.

reduction is included and only around 144 agents have exited the building after 90 s compared to 172 previously.

## *Sensitivity studies*

It is instructive to conduct some sensitivity analysis on the EvacuatioNZ modeling of The Station Nightclub evacuation. There are many aspects that could be investigated as part of such an analysis, for example the distribution of occupants across different nodes, the assumption and use of the random starting position algorithm and the effect of using center-to-center node distances. Here the effect of ignoring the age/sex profiles, the effect of the pre-evacuation time distribution and varying the probability of selecting the preferred exit route are considered where there is no restriction on the use of the platform exit door.

When The Station Nightclub incident scenario is rerun with a fixed unimpeded walking speed of 1.20 m/s instead of the age/sex profiles and the associated functional relationship for unimpeded walking, the mean and standard deviation total clearance time is reduced to $310 \pm 12$ s. This is as might be expected since the evacuation is dominated by the queuing at the constrictions rather than the ability of agents to move quickly. Such an analysis also suggests that using the center-to-center node distance is acceptable, since the travel distance between spaces is not significant in comparison to the queuing.

Galea et al. [7] noted that the pre-evacuation time of the occupants likely had a significant outcome on the number of fatalities. In their work, response times of 25–30 s, 30–35 s and 35–41 s were assigned to agents on the dance floor, in the bar area and in the office and other spaces, respectively. For the EvacuatioNZ sensitivity analysis the pre-evacuation times for agents on the dance floor and sunroom are changed to uniform distributions with a maximum of 25 s and a minimum of 30 s. Similarly a uniform distribution with a maximum of 30 s and a minimum of 35 s is applied to agents in the bar and a uniform distribution with a maximum of 35 s and a minimum of 41 s is applied to agents elsewhere. The mean and standard deviation total clearance time given by EvacuatioNZ is $322 \pm 13$ s which is essentially the same as the original results for The Station Nightclub incident scenario. Since the pre-evacuation distribution used here does not differ much from Galea et al. [7] and the evacuation is dominated by the queuing at the constrictions, it is not surprising to find little difference in the total clearance time.

Finally the probability of agents selecting the preferred exit route is increased from 60% to 70% to correspond with the estimated upper limit of those who used or attempted to use the front entrance door. The mean and standard deviation total clearance time given by EvacuatioNZ is $375 \pm 16$ s. When the probability of agents selecting the preferred exit route is reduced to 50 % to correspond with the typical proportion of agents who used the front entrance door in the NIST Scenario #1 simulations shown in Table 3 then the mean and standard deviation total clearance time given by EvacuatioNZ is $277 \pm 13$ s. As expected, the proportion of agents using the preferred exit route or the shortest exit distance (i.e. the front entrance door and the platform exit door) has a noticeable effect on the total clearance time. If the probability of agents using their preferred route is increased beyond 70% then total clearance times will approach the 493 s that is obtained from the original baseline modeling. So although that baseline result was initially dismissed, a more conservative assessment of the likelihood of agents using the front entrance will effectively give the same result.

## Conclusions

Initial calculations with the EvacuatioNZ network model implementing a shortest route algorithm and a restricted door width for agent flow fails to match the modeling work published elsewhere. However, using door flows without a boundary layer and forcing agents to travel to particular exits or using the preferred exit route capability in EvacuatioNZ allows this model to produce similar results to the equivalent NIST modeling. Interviews and opinions suggest around 60–70% of the occupants attempted to use the front entrance. By prescribing a 60% probability that agents will select a preferred exit path towards the front entrance, the EvacuatioNZ model gives a satisfactory agreement with the NIST modeling. Furthermore by limiting the number of agents who are able to use the platform exit door to the number that are able to egress for the first 30 s also gives satisfactory agreement with the equivalent NIST modeling scenario.

Even with the latest findings published by Fahy et al. it is impossible to determine the exact details of The Station Nightclub incident evacuation. An attempt to model the incident evacuation is a challenge for EvacuatioNZ particularly as it is unable to reproduce a number of the known aspects of the incident evacuation as well as not addressing the effect of the fire on the agents. Using EvacuatioNZ to compare the likely number of fatalities with results from more sophisticated modeling studies and the actual incident gives an over-estimate. The EvacuatioNZ model has not been developed as a forensic tool although it gives some interesting results when it is applied to The Station incident (particularly for the first 90 s). It is not recommended the model be used for a forensic application without a clear understanding of its limitations and by a user who is very familiar with the model's capabilities.

It would be inappropriate to claim that this work has validated EvacuatioNZ. Instead this work forms part of an ongoing comparative assessment of the model and provides a benchmark against other similar modeling work that has been carried out by other researchers. The article illustrates some of the capabilities of the EvacuatioNZ model and network models in general. It shows that a network-type model can provide similar results to various fine grid/continuous models but those results are reliant on the user understanding the limitations of the model and aspects associated with a particular event. Selecting the likely probability that agents will use a specified preferred route and the inclusion of boundary layers are critical in this scenario in comparison to the detailed movement modeling aspects.

## Acknowledgement

The author would like to thank Dr Erica Kuligowski for her knowledge of the NIST evacuation modeling work described in this article.

## Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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