Proceedings of the 2016 Winter Simulation Conference
T. M. K. Roeder, P. I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick, eds.

MANAGING EGRESS OF CROWD DURING INFRASTRUCTURE DISRUPTION

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ABSTRACT

In a large indoor environment such as a sports arena or convention center, smooth egress of crowd after an event can be seriously affected if infrastructure such as elevators and escalators break down. In this paper, we propose a novel crowd simulator known as SIM-DISRUPT for simulating egress scenarios in non-emergency situations. To surface the impact of disrupted infrastructure on the egress of crowd, SIM-DISRUPT includes features that allows users to specify selective disruptions as well as strategies for controlling the distribution and egress choices of crowd. Using SIM-DISRUPT, we investigate effects of crowd distribution, egress choices and infrastructure disruptions on crowd egress time and measure efficacies of different egress strategies under various infrastructure disruption scenarios. A real-world inspired use case is used to demonstrate the usefulness of SIM-DISRUPT in planning egress under various operational conditions.

1 INTRODUCTION

Efficient egress of crowds from an indoor facility such as a sports arena or convention center is a challenging management problem. Proper working conditions of infrastructure such as elevators, staircases, escalators and doorways are critical in ensuring smooth egress, and disruptions to these infrastructure change egress pattern thereby creating or aggravating congestion. Crowd congestion due to infrastructure disruption will result in negative customer experience for the venue, and severe crowd congestion may even give rise to safety issues (such as accidents and stampede). From the management standpoint, it is interesting to study how the egress behavior of crowds varies with different infrastructure disruption scenarios, and to evaluate the performance of egress metrics (such as egress time) under different crowd management strategies.

The movement and egress of indoor crowd has been studied in Thompson (1994), Klüpfel, Schreckenberg, and Meyer-König (2005), Nara and Torrens (2007), Schadschneider, Klüpfel, Kretz, Rogsch, and Seyfried (2009), Bellomo, Piccoli, and Tosin (2012), Duives, Daamen, and Hoogendoorn (2013). Computer simulation platforms are also known for studying crowd in indoor environments such as auditorium (Forell et al. 2013), high-rise buildings (Wu and Huang 2015) and sports stadium (Graat et al. 1999). Computational techniques such as multi-agent systems (Pan et al. 2005), cellular automaton (Klüpfel 2003), pattern-based mixed integer dynamic network flow model (Bretschneider and Kimms 2012), stochastic dynamic programming (Luh et al. 2012) and vertical mixing evacuation model (Huang et al. 2014) are explored. Most of these works are focused on peace-time (Ball 2012, Gwynne and Siddiqui 2013, Akinwande et al. 2015) and crisis-time (Semaan and Mark 2011, Abdelghany et al. 2014) scenarios. However, works addressing congestion due to abrupt infrastructure disruption when crowd is egressing the facility are still rare and may be emerging.

To address such needs, this work introduces a novel special-purpose multi-agent simulator known as SIM-DISRUPT. Built using Repast Simphony (North et al. 2013), SIM-DISRUPT is capable of simulating large crowd comprising heterogeneous agents in three-dimensional indoor environments. SIM-DISRUPT allows users to select infrastructure disruption scenarios, define the distribution and egress choices of the crowd. Using SIM-DISRUPT, the efficacies of proposed strategies for managing the egress of crowd are evaluated for a wide variety of egress scenarios. By analyzing these experiments we are able to assess the relative importance of various factors involved in the design of egress management strategy.

The presentation of this work continues with the survey of related works in Section 2. This is followed by the definition of the research problem in Section 3. SIM-DISRUPT is then introduced in Section 4. Details on the proposed strategies for managing egress are described in Section 5. This is followed by details on the design of egress scenarios using SIM-DISRUPT in Section 6. Results of experiments based on these scenarios are analyzed and discussed in Section 7. Last but not least, we draw some conclusions for this work in Section 8 and motivates a couple of future work.

2 RELATED WORK

Thompson (1994) is one of the earliest survey of crowd movement and egress. This survey contains earlier works on the analysis of crowd movement and computer modeling approaches. Klüpfel et al. (2005) describe methods for categorizing existing crowd movement and egress models. A wiki-based approach and web pages of similar projects are also described. Nara and Torrens (2007) explore analytical methodologies for examining crowd egress behaviors and quantifying egress efficiency. In particular, the work examine the effect of egress route and pedestrian speed on egress efficiency. Schadschneider et al. (2009) describe the observed phenomena and crowd modeling approaches. Two safety analysis for egress from aircraft and football stadium are also described. Bellomo et al. (2012) motivates the mathematical modeling of crowd dynamics. The expressed view is that mathematical models should be built on the correct interpretation of interaction dynamics, not from the use of empirical data.

Forell et al. (2013) compare several well-known simulation models within the setting of auditorium crowd. Duives et al. (2013) assess crowd simulation models in terms of known crowd phenomena to determine their suitability for high density crowds. Sagun et al. (2011) consider the use of computer simulations and building guidance to enhance the evacuation performance of buildings. Gwynne and Siddiqui (2013) use analytical and simulation tools to investigate the relationship between low-level actions of agents and the high-level emergent conditions. Abdelghany et al. (2014) integrate simulation and optimization techniques for modeling the evacuation of large crowd from facilities with multiple exits. Wu and Huang (2015) proposed a control volume model to simulate the dynamic of crowd evacuating from high-rise buildings. Mukherjee et al. (2015) proposed a Lagrangian approach for modeling and analyzing crowd dynamics.

Graat et al. (1999) investigate the effects of motivation level and gradient of stairs on egress time in emergency situations at a sports stadium. Ozel (2001) examine how time pressure and environmental stress affect the ability of the crowd to properly process environmental cues. Semaan and Mark (2011) conduct ethnographic study on the use of ICT for resolving infrastructure disruption in a war zone. Ball (2012) studies the movement of crowd in cities using data for the planning of public spaces. Hofinger et al. (2014) identify physical, cognitive, motivational and social factors relevant for fast and safe evacuation. The authors have also gathered human factors from the other domains for explaining the behavior of crowd in emergency situations.

Klüpfel (2003) proposed a cellular automaton model for crowd movement and egress simulation. More recently, Boukas et al. (2015) also proposed a cellular automaton model that assesses human behavior in emergency situations. A mobile robot uses the simulated output to guide crowd out of emergency situations. Pan et al. (2006) uses a multi-agent simulation framework to study human and social behavior. Manley and Kim (2012) proposed a decision support (DS) tools for assessing and optimizing emergency response plans for rare but catastrophic events. The DS tool can be used to evaluate evacuation strategies.

Luh et al. (2012) proposed a divide-and-conquer approach to guide groups of evacuees to safety. Stochastic dynamic programming and roll-out scheme are used to optimize egress routes in that work. Bretschneider and Kimms (2012) proposed a pattern-based mixed integer dynamic network flow model that restructure traffic routes such that the safety and egress efficiency of the crowd are optimized. Huang et al. (2014) proposed a vertical mixing evacuation model that incorporate statistical information such as the elevator waiting time and the percentage of occupants at the elevators. This work also evaluates eight evacuation strategies using specific scenarios. Most recently, Akinwande et al. (2015) proposed a routing algorithm driven by quality-of-service metric for heterogeneous crowd.

Most aforementioned works are motivated by the needs of egress planning during emergency. Much less attentions are paid to day-to-day, non-life-threatening scenarios under different operational constraints; in particular, when certain parts of infrastructure experience unexpected disruptions. This is the gap in the literature that we aim to address.

3 PROBLEM DEFINITION

3.1 A Motivating Problem

Imagine an end-of-day scenario where two groups of conference delegates are egressing from a common conference venue. On this day, two large-scale conferences with combined attendance of thousands of delegates are organized over three floors of a sprawling convention center. To go to the venues of their conference banquets, one group of delegates is told to gather at the south lobby while the other group of delegates is told to gather at the east lobby.

In normal scenario, delegates at all levels can use escalators, staircases and elevators to reach the lobbies. However, several disruptions happened to the infrastructure on this day: two elevators broke down, affecting all levels; and at level 3, one of the two escalators going down to the ground floor also broke down, leaving delegates at level 3 with only two staircases and one downward-traveling escalator. Level 3 thus becomes an egress bottleneck, and more and more delegates leaving the meeting venue are stuck at level 3, with congestion backlogs going all the way back to the higher levels.

3.2 The Research Questions

Following the motivating example, we propose two lines of research. Firstly, we are interested in understanding the impact on egress time when the crowd is distributed differently and when the crowd has different egress choices. Secondly, we are interested in the impact on egress time when different parts of the infrastructure experience disruptions and then determine the efficacy of different egress strategies on these egress scenarios.

In both cases, we recognize that there are a number of external and internal factors that could potentially interact with both infrastructure disruptions and egress strategies; for example, the physical distribution of crowd, egress choice, information availability, and load-balancing strategies. The parameter space of these interacting parameters turns out to be non-trivial, and a series of simulation studies will be necessary to address these two research questions.

The design of our agent-based simulator that incorporates the parameter design space mentioned above is discussed in Section 4. We then discuss our proposed egress strategies in Section 5. The design of egress scenarios is described in Section 6 to facilitate computational studies.

4 THE CROWD SIMULATOR

As reviewed in the literature survey section, our agent-based crowd simulator, SIM-DISRUPT, is not the first in crowd simulation. However, it does put together a number of elements that are not commonly seen in the existing works. In particular, we emphasize on the following features:

- Three-dimensional building model: All floors and facilities are situated in a three-dimensional space. This allows buildings with odd shapes to be accurately modeled. This also allows us to easily model a wide variety of ways for visitors to move between floors, e.g., stairs, elevators, escalators, conveyor belts.
- Fast prototyping using floor plan: Instead of manually creating floor layouts, we can efficiently create floor physical models by importing color-coded floor plans.
- Microscopic crowd movement: Visitor agents are modeled physically, with obstacle avoidance and path planning capacities. We can also easily allow agents to possess different levels of information. We also consider agent's queuing behaviors at facilities (such as waiting for elevators).

For the rest of the section, we will focus on explaining these design features.

4.1 The Crowd Model

The Agents: The crowd is modeled as homogeneous agents moving in a multi-floor indoor environment. The most important agent class in our simulation is visitor agents. As our focus is on egress, agents will be initialized to occupy certain spots in the building, while each of them will be given a time to egress and egress choice.

Agents in our model follow a three-tier movement logic. At highest level, an agent will generate a path that will lead to his destination (given his knowledge of the environment, which can be incomplete). At middle level, an agent will try to execute the planned path, yet if the originally planned path is obstructed or congested, a feedback will be sent to the path planning module, and the path can be regenerated. The lowest level is obstacle avoidance, which allows an agent to sense the space around him and avoid physical obstacles and other visitor agents.

Path Planner: The agents move from point A to point B in a greedy manner. The path planning algorithm we utilized is a variant of A* algorithm. The major difference from the classical A* algorithm is the introduction of *navigation mesh* (Snook 2000). Navigation mesh is essentially a collection of connected triangles, and such triangularization can be applied to any physical environment. After the creation of navigation mesh, the underlying graph of an environment is then constructed using triangles: triangle centroids as nodes, and linkage based on adjacency. The A* algorithm is executed on this derived graph.

Obstacle Avoidance: Agent's obstacle avoidance behaviors are modeled using both the Boids model (Reynolds 1987) and the reciprocal velocity obstacles (RVO) model (Van den Berg et al. 2008). The high-level idea of the Boids model is for agent to perform three actions: 1) steering away from other local agents, 2) aligning to local agents' average direction, and 3) moving to the average position of local agents.

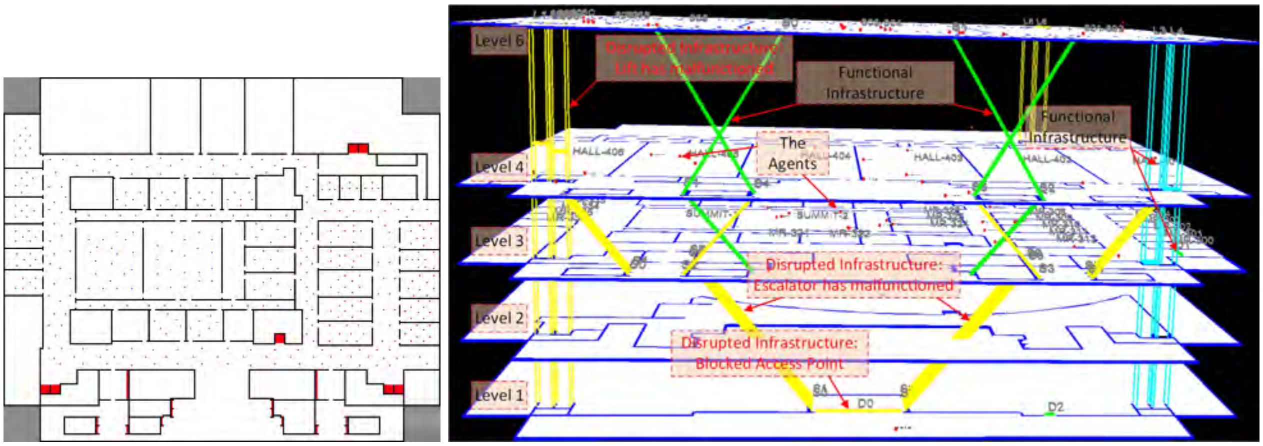
Although Boids model is one of the most well-adopted model for emulating flocking behaviors, it's not directly applicable for simulating visitor behaviors for our purpose, as visitors usually have specific goals in mind, and not just moving in accordance to local crowd. This is where the RVO model can complement the Boids model. Agents in the RVO model will anticipate other nearby agent's velocity (both speed and direction), and maneuver to avoid these agents. The avoidance is implemented by defining *velocity objects* (VOs), which are essentially cones that include potential locations that could be covered by nearby agents, based on their current velocities. Agents would treat VOs as real obstacles and move around them. Our implementation of these two methods are standard, thus we will not go into their technical details.

A special feature that we introduce in our model is the queuing at capacitated facilities such as elevators. Agents are programmed to recognize these facility, and if utilizing these facilities is in their plans, they will join the queue. The management of these queues is handled by the corresponding objects in the environment (to be discussed next).

4.2 The Environment Model

Our simulation environment contains both dynamic and static objects. Dynamic objects refer to any objects that move, which include visitor agents, and facilities such as elevators. Static objects refer to fixtures, such as floors, stairs, escalators, conveyor belts (if any), and doorways (served as egress destination for visitor agents).

To speed up the model creation process, we allow floor models to be created using color-coded floor plan (a sample is provided in Figure 1a). In Figure 1a, the black lines represent walls, white blocks are accessible space, red dots are location sensors, and red blocks are elevators. With floor plans like this, a floor in the 3D building model is then automatically generated in Repast Simphony 3D environment. After all floors are generated, we still need to define the connections between floors, yet it will be much simpler than having to create everything from scratch.



(a) A sample of color-coded floor plan. (b) A 3D building model.

To define connection between floors, we need some additional parameters. For stairs, escalators, and conveyor belts, we need to specify direction (going up or down), starting and ending coordinates (floor index plus x and y in the floor), and maximum speeds that agents can travel on them. For the elevator, we need to specify its operational range (serving which floors), maximum capacity, and speed. The elevator control logic is defined as a module to suit different building models. The basic logic that we initially adopted is following the first-come-first-serve principle: when an agent requests for the elevator service at any level, the closest available lift will respond to request, and once the agent is picked up and the lift moves toward the destination floor, it will serve any visitors requesting for service along the same direction. A queue will be formed and maintained by the elevator agent if no lift is currently available.

5 MANAGING EGRESS OF CROWD

This section describes strategies for influencing the egress of crowd when there is infrastructure disruption. The strategies are composed using policies for controlling information and for balancing the number of agents (the load) waiting to use the infrastructure.

5.1 The Information Control Policy

Information on the status of the infrastructure can be used to influence the egress pattern of the crowd. When the simulation begins, the status of the infrastructure in the mind of the crowd is *functional*. Information control (IC) policies can be designed to modify the status of the infrastructure in the mind of the crowd. Specifically, this work investigates the effect of using *partial* and *complete* information policies on the egress pattern of the crowd.

Partial Information Policy (Partial-Info): This IC policy does not update the agents on the status of the infrastructure. The agents will know about the status of infrastructure only when it is at the infrastructure. The agents will navigate to the next nearest infrastructure only when that infrastructure is *disrupted*. In the event that the alternative doorway is also *disrupted*, the agents will not return to the previous infrastructure because it remembers that the infrastructure is already *disrupted*.

The agents are said to have *partial* information on the status of the infrastructure as the status of the infrastructure is updated gradually. This is the default information control policy.

Complete Information Policy (Complete-Info): This IC policy updates the agents on the status of the infrastructure when the agents begin to egress the building. Using the updated status of the infrastructure, the agents will move directly to a *functional* infrastructure. Depending on the availability and spread of the *functional* infrastructure, congestion may form rather quickly at those infrastructure.

5.2 The Load Balancing Policy

The load balancing (LB) policies influence the behavior of agents at the infrastructure. As the agents move greedily, many agents can be seen at the same infrastructure. Infrastructure such as the elevators and the escalators have limited capacities. The need to wait to be served by these infrastructure can delay the egress of agents. Hypothetically, this means the egress time of crowd may be improved by balancing the load at the infrastructure.

No Load Balancing (No-Balancing): The agents move greedily to their egress choices. Using this load balancing policy, the agents do not seek out a less congested infrastructure when they are at a congested infrastructure. This is the default load balancing policy.

Load Balancing (Load-Balancing): The agents still move greedily to the egress choices. Using this load balancing policy, the agents are aware of the congestion at the infrastructure. When the agents are at a congested infrastructure, the agents will seek out the next nearest infrastructure to go to their egress choice.

5.3 The Egress Strategy

The egress strategies are composed using an information control policy and a load balancing policy. Four egress strategies seen in Table 1 are used in the second part of this work to investigate the efficacy of the egress strategies on the egress patterns of the crowd. The efficacy of the egress strategies is measured using the egress time of the crowd.

Table 1: The Egress Strategies.

Egress Strategy	IC Policy	LB Policy
Default	Partial-Info	No-Balancing
CI	Complete-Info	No-Balancing
LB	Partial-Info	Load-Balancing
Integrated	Complete-Info	Load-Balancing

Table 2: The Infrastructure Disruption (ID) Schemes.

Scheme	Elevators	Escalators	Doorways
All-Green	None	None	None
All-Disrupted	Disrupted	Disrupted	Disrupted
Doorways-Disrupted	None	None	Disrupted
Escalators-Disrupted	None	Disrupted	None
Elevators-Disrupted	Disrupted	None	None

6 DESIGN OF EGRESS SCENARIOS

Egress scenarios are designed by composing the schemes for infrastructure disruption, crowd distribution and egress choices. The schemes are introduced in Section 6.1. The egress scenarios designed using these schemes are described in Section 6.2.

6.1 The Schemes

The schemes used to design the egress scenarios are the infrastructure disruption schemes, the crowd distribution schemes and the egress choice schemes. The details of these schemes are described in the following paragraphs.

Infrastructure: Infrastructure such as the elevators, the escalators and the doorways can be disrupted. The design choice is for either 100% disruption or no disruption of a particular type of infrastructure. Table 2 shows the infrastructure disruption (ID) schemes. A point to note here is that the crowd can still egress the building using the emergency exits when the two doorways are blocked. Emergency exits are always available in all building and they can never be blocked. Therefore, in the worst scenarios, the crowd is always able to egress the building using the emergency exits.

Table 3: The Crowd Distribution (CD) Schemes.

Scheme	Level 3	Level 4	Level 6
All-Levels	33%	33%	34%
Only-Level6	0%	0%	100%
Only-Level4	0%	100%	0%
Only-Level3	100%	0%	0%

Table 4: The Egress Choice (EC) Schemes.

Scheme	Bus-Taxi	Train	Mall
All-Modes	33%	33%	34%
All-Mall	0%	0%	100%
All-Train	0%	100%	0%
All-Bus-Taxi	100%	0%	0%

Crowd Distribution: A fixed percentage of agents is distributed over the 3^{th}, 4^{th} and 6^{th} floor of the building. At each floor, the agents are uniformly distributed among the rooms. Table 3 shows the crowd distribution (CD) schemes based on this design choice.
Egress Choice: The egress choice determines how the crowd egress the building. Infrastructure such as elevators, escalators and staircases may be used by the crowd in this process. As mentioned in Section 4.2, the egress choices are matched to the doorways. The design choice here is to spread the crowd based on egress choice (EC) schemes seen in Table 4.

6.2 The Egress Scenarios

The egress scenarios are designed using five ID schemes, four CD schemes, four EC schemes, two IC policies and two LB policies. Fully permuting these schemes and strategies gives a total of 320 egress scenarios. Such a design choice is made to design egress scenarios that mark the boundary conditions of the research problem.

7 THE EXPERIMENTS

Experiments are performed to investigate the research problem described in Section 3.2. The setup of the experiments are described in Section 7.1. The results used for investigating the effect of crowd distribution and egress choices are described in Section 7.2 while the results used for investigating the efficacy of egress strategies are described in Section 7.3.

7.1 The Experiment Setup

Experiments are performed by acting out the egress scenarios using the SIM-DISRUPT crowd simulator. The egress time of the crowd is collected as a primary quantitative measure of the scenarios. To cancel out the stochastic effect of the scenarios, experiments on each scenario are conducted several times. The design choice here is to run the experiments for five times on each scenario. The egress times from the runs for a particular scenario are aggregated to give the mean values.

A fixed number of agents is predetermined to form the crowd. The crowd used in this work comprises $1,000$ agents. These agents are distributed according to the crowd distribution schemes outlined in Table 3 in the multi-floor indoor environment illustrated in Figure 1b. The number of agents at each floor and each room are specified explicitly. The agents in each room are then placed in an uniformly random manner.

To preserve the distribution of the crowd, the agents do not move from its initial position until it begins to egress the venue. The agents are programmed to egress the venue at the same time. This design choice is made to amplify the impact of infrastructure disruption on the egress of crowd. At egress time, the agents move towards to their own egress choices. The greedy path that brings the agent from its current position to the egress choices may comprise the use of infrastructure such as elevators, escalators, staircases and the doorways.

Time is measured in terms of seconds. Each run of the egress scenario is designed to last for $2,400$ seconds. The total number of agents at the venue is known from the onset. The remaining number of agents at the venue is collected at every timestep. The total number of agents and the remaining number of agents are used to derive the egress percentile of the crowd. The cumulative sequence of egress time forms the egress profile of crowd in a particular scenario. The egress profiles are used to gain insight into the research problem defined in Section 3.2.

7.2 Crowd Distribution and Egress Choices

To investigate the effect of crowd distribution and egress choices on the egress times, experiments are conducted using four crowd distribution and four egress choice schemes. These schemes are designed to mark the boundary conditions of the research problem. The plots seen in Figure 2 and Figure 3 do not include results from scenarios with disrupted infrastructure.

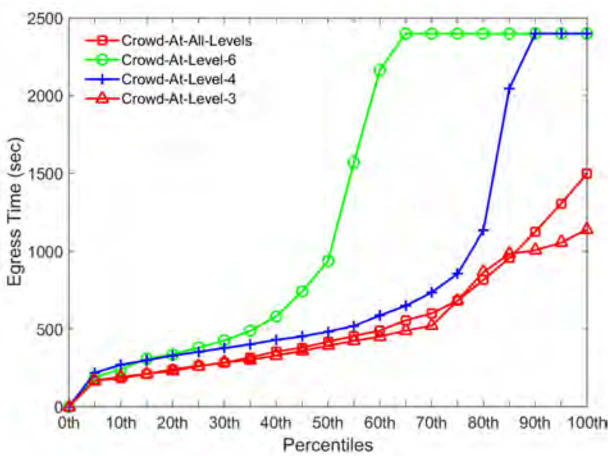


Figure 2: The egress time of crowd due to different crowd distributions.

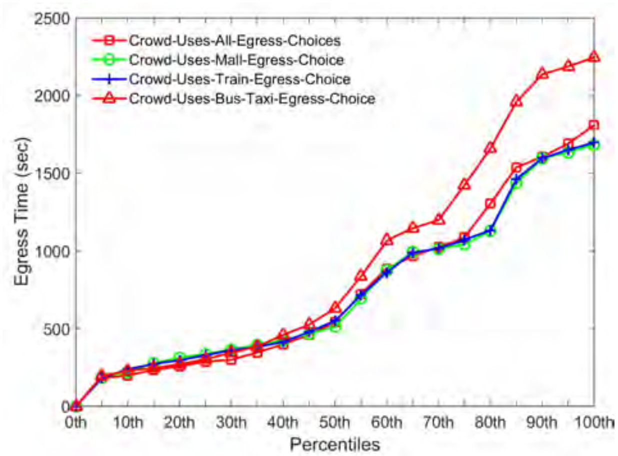


Figure 3: The egress time of crowd due to different egress choices.

The effect of different crowd distribution (CD) on the egress time of the crowd is seen in Figure 2. The egress profile for each CD is aggregated using the egress profiles of all the EC schemes. As seen in Figure 2, only 65^{th} and 90^{th} percentiles of the crowd has egressed for crowd seen only at level 6 or level 4 respectively. The crowd seen at all levels needs around $1,497$ seconds to reach the 100^{th} percentile while the crowd seen at level 3 reaches the 100^{th} percentile at $1,138$ seconds.

The observations made on the effect of crowd distribution are within expectation. The egress time of crowd at level 6, level 4 and level 3 are directly proportional to the proximity to the doorways. For these experiments, the crowd is designed to egress through the doorways at level 1 and level 3. Given such a design choice, the crowd at level 3 is expected to have the smallest egress time. The egress time of crowd at all level is just slightly longer than the crowd at level 3 because the crowd is uniformly distributed throughout the levels. This way of distributing the crowd has helped in the egress of the crowd. All of these observations show that the distribution of the crowd has significant effect on the egress time.

The effect of different egress choices (EC) on the egress time of the crowd is seen in Figure 3. In this case, the egress profile for each EC is aggregated using the egress profiles of all the CD schemes. As seen in Figure 3, the crowd with the mall and train egress choices reach 100^{th} percentile at around $1,683$ seconds and $1,697$ seconds respectively. The crowd with bus-taxi egress choice requires around $2,246$ seconds to reach 100^{th} percentile. The crowd that is evenly distributed to all the egress choices needs around $1,809$ seconds to egress the building.

The effect of the egress choice schemes appears to be less varied than the crowd distribution schemes. In particular, the egress time of crowd with mall and train egress choices is rather closely matched because these two egress choices are at level 3. Crowd with the bus-taxi egress choice is expected to have the longest egress time because the doorway matched to this egress choice is at level 1. The crowd has to travel longer distance and use more infrastructure to get there. The aggregated effect of all the egress choices on the egress time is seen for the crowd with all the egress choices. Such observations also confirm that the egress choices of the crowd has significant effect on the egress time.

7.3 Infrastructure Disruption and Egress Strategies

To investigate the effect of egress strategies, experiments are conducted using the infrastructure disruption (ID), crowd distribution (CD) and egress choices (EC) schemes described in Section 6.1. The plots seen in Figure 4 are aggregation of the ID, CD and EC schemes. The focus here is on showing the effect of infrastructure disruption and how egress strategies can help to reduce the egress time of the crowd when there is infrastructure disruption.

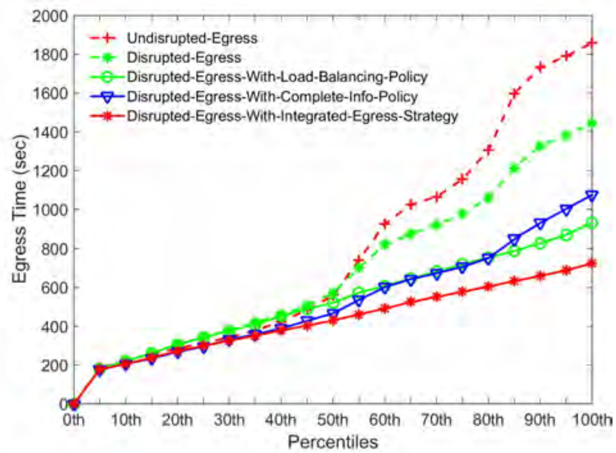


Figure 4: The egress time of crowd due different egress strategies.

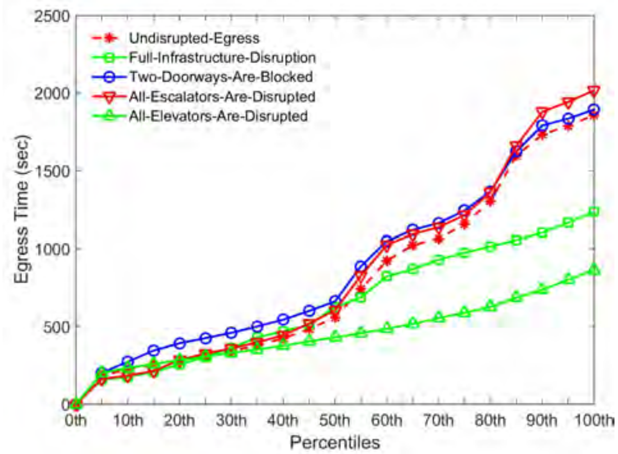


Figure 5: The egress time of crowd due different infrastructure disruption

Two main observations can be made on the plots seen in Figure 4. Firstly, the crowd requires just around $1,445$ seconds to reach the 100^{th} percentile when there is infrastructure disruption. On the contrary, the crowd requires 28.65% more time to reach the 100^{th} percentile when there is no infrastructure disruption. The crowd can egress the building around 49.83% faster using the integrated egress strategy when there is infrastructure disruption. The crowd egress the building using around 35.71% faster and 25.61% faster using just the Load-Balancing policy or the Complete-Info policy respectively.

The efficacy of egress strategies is evident from the plots seen in Figure 4. Among the three egress strategies, the integrated egress strategy is the most effective. This effectiveness of the integrated egress strategy may be attributed more to the Load-Balancing policy than the Complete-Info policy. This is because the crowd egress the building faster using just the Load-Balancing policy than just the Complete-Info policy. The crowd is also expected to egress the building slower when unguided than when it is guided by the egress strategies. However, it turns out the crowd egress the building faster when there is infrastructure disruption than when there is no infrastructure disruption.

Such a phenomenon can be explained using the plots seen in Figure 5. Based on the baseline egress time of around $1,859$ seconds, the crowd requires around 53.47% less time to egress the building when the elevators are disrupted. The egress time increases by around 1.88% when two doorways are blocked and by around 8.61% when the escalators are disrupted. The egress time reduces by 33.46% when all the infrastructure are disrupted. The impact of disrupted elevator on the egress time is clearly evident for when all the infrastructure is disrupted.

8 CONCLUSION

This work introduces a crowd simulator known as SIM-DISRUPT. It is used to investigate two research issues. The first research issue investigate the effect of crowd distribution and egress choices of crowd on the egress time of crowd during infrastructure disruption. The second research issue investigate the effect of egress strategies on the egress time of crowd for the same egress scenarios.

To investigate these two research issues, egress scenarios are designed using four crowd distribution schemes, four egress choice schemes and five infrastructure disruption schemes. The design choices of these schemes are made to mark the boundary conditions of the problem. The egress strategies are composed using two information control policies and two load balancing policies. Based on all permutation of these schemes and policies, there is a total of 320 egress scenarios for the experiments.

Two sets of experiment results are presented in this work. The first set of results are used to investigate the first research issue. The results from egress scenarios when there is no infrastructure disruption are used for this part of the work. The results show the distribution of the crowd has a more significant impact on the egress time of the crowd than the egress choices of the crowd.

The second set of results are used to investigate the second research issue. The results from egress scenarios based on the four crowd distribution schemes, four egress choice schemes and five infrastructure disruption schemes are used for this part of the work. The results show the egress strategies are effective in reducing the egress time of the crowd when there is infrastructure disruption. A surprise observation is that the crowd egress the building faster when there is infrastructure disruption than when there is no infrastructure disruption. Closer investigation of the results shows the disruption of the elevators can actually significantly reduce the egress time of the crowd. This is because the elevators have limited carrying capacity and no time is wasted waiting for the elevators when the elevators are disrupted.

Interesting insights are gained from the results of simulation performed using our SIM-DISRUPT crowd simulator. Such insights should be useful to the venue operator in preparing the egress scenarios when there is infrastructure disruption. The progress made in this work encourages more in-depth investigation on the egress of crowd from more complex indoor environments. The surprise outcome on the disrupted elevators may mean the venue operator can choose to disrupt certain infrastructure to speed up the egress of crowd. Such a hypothesis is interesting and worth further investigation.

Acknowledgment

This work is funded by the National Research Foundation, Singapore under its Corp Lab @ University scheme.

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