Proceedings of the 2019 Winter Simulation Conference
N. Mustafee, K.-H.G. Bae, S. Lazarova-Molnar, M. Rabe, C. Szabo, P. Haas, and Y.-J. Son, eds.

ANALYZING EMERGENCY EVACUATION STRATEGIES FOR LARGE BUILDINGS USING CROWD SIMULATION FRAMEWORK

Imran Mahmood
Talha Nadeem
Faiza Bibi
Center for Research in Modeling Simulation (Crimson)
School of Electrical Engineering and Computer Science
National University of Sciences & Technology
Sector H-12, Islamabad, 44000, PAKISTAN

Xiaolin Hu

Department of Computer Science
Georgia State University
Atlanta, GA, 30303, USA

ABSTRACT

The occurrence of natural or man-made emergencies can be quite complex and demand flawless preparedness, through tested strategies, in order to ensure the safety of the individuals. For large-scale infrastructures, whether commercial or residential, having a reliable evacuation strategy is crucial. Formulation and evaluation of these evacuation strategies is however a daunting challenge. In this paper, we propose a Crowd Simulation and Analysis framework for the formulation and evaluation of effective evacuation strategies in large buildings, using real-scale building structures and agent based approach. We further propose an algorithm to devise an evacuation strategy. We first demonstrate the functionality of our algorithm using a simplistic example and then apply the algorithm in a campus evacuation case study using three scenarios. The main goal of this research is to assist regulatory authorities in developing effective disaster management plans through the use of M&S methods and tools.

1 INTRODUCTION

An emergency evacuation is defined as the immediate act of egress or escaping of pedestrians from an area containing a threat (Jim Burtles 2016). That area can be an open public gathering place such as stadium or it can be a multistoried building. The scale of an emergency evacuation ranges from small scale evacuations such as the evacuation of a building due to an earthquake, to large scale evacuations such as the evacuation of a city due to flooding. In the case of emergency evacuation of buildings, an evacuation is considered to be complete and optimal once all the occupants of the building have safely exited the building in the shortest possible time based on the scenario. Evacuation plans are devised beforehand and are implemented using different techniques, including evacuation guidelines displayed using sign boards and emergency responders deployed at various locations throughout the building.

There have been thousands of human casualties around the world, all of which point to inadequate planning of emergency evacuations of buildings. Pakistan is ranked amongst the top 10 in the list of countries with the highest number of deaths caused by natural or manmade disasters, which could have been avoided if sound emergency response management and evacuation plans were in place. Emergency evacuations are not just restricted to natural disasters. Manmade disasters also require the quick and timely evacuation of inhabitants which can otherwise result in a large number of casualties (Christchurch 2019). The formulation and implementation of optimal emergency evacuation strategies is of outmost importance in context to the safety of the inhabitants of a building. Accidents can be minimized by preplanning optimal strategies for the building evacuation in the case of both natural and man-made disasters. The damages during emergency situations can be avoided if the organizations are properly trained for the Public Safety & Security (PSS). PSS is usually expressed as a governmental responsibility but can be incorporated within a large organization, or residential societies and primarily aims at prevention and protection of the public from dangers like disasters, health risks, crimes or terrorism. Public Safety refers to the welfare and protection of the general public against natural or man-made disasters and pandemics or environmental hazards whereas Public Security ensures the protection of communities against threats related to crimes, law & order, terrorism and mass incidents (riots). These services bring value to society by creating a stable and secure environment and protection to the people and assets at local, regional and national level. Figure 1 overviews different roles of a PSS organization. An effective PSS infrastructure focuses on the timely Monitoring of potential calamities of any kind, mitigate these risks through effective Preparedness and Incidence Response Management.

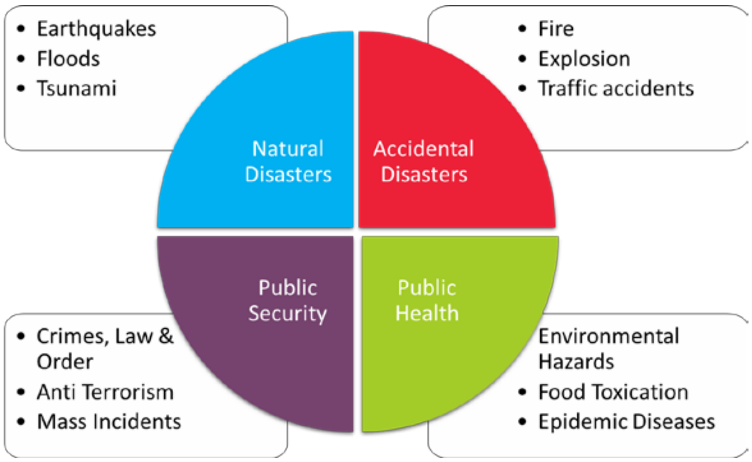

Figure 1: Public Safety and Security.

Traditionally, evacuation drills are conducted to increase the chances of survival of the regular inhabitants of a particular building. The inhabitants of that building are made aware of the safest and shortest emergency routes of the building which decreases the chances of accidents when subjected to a real emergency evacuation. It is however tedious, disruptive and time consuming to conduct regular emergency drills.

The domain of Modeling and Simulation (M&S) plays a vital role in this regard with many additional benefits. M&S methods and tools provide risk-free and time independent environments which allow effective and thorough analysis, without disrupting the real-world. In many cases, we can't simply afford to find the right solutions by experimenting with the real world. Experimenting or making changes in the real world may be too expensive, dangerous, or just impossible. It is therefore quite challenging to experiment emergency scenarios in real environments and to formulate the evacuation plans for public safety. On the contrary, simulation models are low cost, time independent and offer a harmless experimental environment, thus becoming useful in replicating real scenarios in the risk-free world, where modelers can perform different experiments to gain the insights of the system and compare different strategies to determine the optimal solutions. Modeling allows for the implementation of a real-world system into a risk free world for the purpose of studying the system in detail, gain insights, compare various alternatives or conditions to study the behavior of the real world system. With the increased accessibility of abundant computational power, M&S domain has encompassed almost all the industrial domains, and has specially proven to be valuable in the domain of emergency disaster management.

Evacuation modeling purposefully abstracts and simplifies the pedestrians as entities, their individual as well as collective behaviors within walled structures, activities, and their responses to different possible scenarios within large building structures. Crowd Simulation focuses on the execution of multi-scenario evacuation strategies using all available exits, identifying and overcoming possible bottleneck areas in the building, emergence of unforeseen behavior of the crowd as a whole and much more. Crowd Simulation approaches have gained renewed interest of the communities to model and simulate different scenarios and replicate fire breakouts, earth quakes, or insurgency attacks in a building. Optimal evacuation plans can be devised and tested exhaustively, before they are implemented in the real-world. There are numerous modelling paradigms which can be used for the purpose of crowd simulation (Vermuyten et al. 2016). These are mainly categorized into Macro, Meso and Micro scale depending on the crowd size and the granularity of the structures and the behaviour of the modeled elements (Mahmood, Haris, and Sarjoughian 2017). Crowd simulation has been effective in modeling and analyzing behavior and movements of dense crowds in different areas such as: shopping malls, airports, stadiums and parks, therefore can help in adapting better strategies to manage the crowd and reduce causalities. Incidents in largely crowded events are worsened due to key contributing factors including: high densities above 7 or 8 persons per square meter, complex motion flows, stampedes, lack of emergency evacuation structures, untrained mob and slow in-time rescue. With the help of a simulated evacuation model, crucial factors that are hidden or overseen in real life scenarios can be identified through the emergent behavior and interaction of the modeled agents.

In this paper, we propose a Crowd Simulation and Analysis framework for the emergency evacuation modeling, simulation, visualization, analysis and the optimization of large buildings, using real-scale building structures and agent based approach. We further propose an algorithm called: *Nearest Exit Shortest Time* (NEST), in order to devise an evacuation strategy, that not only assigns exits to different regions based on shortest distances but also load balances the crowd at the different exits by using different time windows. We demonstrate the functionality of our algorithm using a simplistic example and apply the algorithm in a campus evacuation case study using three scenarios. Our algorithm outperforms random evacuation and scales up when the population is increased. The main goal of this research is to assist regulatory authorities, and PSS organizations at local, regional or national level, in devising effective disaster management plans through the use of M&S methods and tools.

The rest of the paper is organized as follows. Section 2 describes the related work. Section 3 describes the proposed framework. Section 4 presents the case study and simulation results. Finally, Section 5 frames the summary and conclusions.

2 RELATED WORK

This section projects some work already published in the area of Emergency Evacuation using different modeling and simulation techniques.

2.1 Crowd Simulation Approaches

Agent based approach has been widely used in literature to study the emerging behaviour of crowds. Wagner and Agrawal (Wagner and Agrawal 2014) implemented an agent based model to address preparedness and planning in case of fire disasters in a mass gathering such as concerts. The Model allows for customization of concert venue layout and testing of different scenarios. Real time simulations combined with agent based are used to study and predict the emerging behavior of the crowd with more accuracy.

Chen et al. (Chen et al. 2017) proposed a real time agent based simulation framework, based on live position tracking from a surveillance video. An algorithm is proposed to solve the challenge of missing human positions in video frames, and to generate optical flow of human moving patterns based on density estimation.

Another approach to study crowd behavior involves assigning different roles to entities in a crowd. Zhao et al. (Zhao, Zhong, and Cai 2018) introduced roles of leaders and followers to model human behavior in high density crowds. This data driven model is able to simulate the collective behavior of crowd such as lane formation in a realistic way. Incorporating optimization strategies in evacuation process improves the efficiency of process. Hu et al. (Hu et al. 2018) proposes a framework to optimize crowd evacuation using a feedback system based on genetic programming. This approach shows a shorter evacuation time and reduced congestion but it is applicable only to scenarios flexible enough to allow intervention in evacuation planning and moving speed.

Emerging behavior of lane formation and shock-rare faction waves on encountering hurdles is observed and their the dynamics were studied by (Abdelghany et al. 2018). The flow of pedestrians in a crowded tunnel was simulated using micro-simulation model and cellular automata. Their findings show that in a high volume elongated area like a tunnel, flow dynamics of pedestrians show a very similar behavior to that of vehicular flow.

In the event of mass gatherings such as Hajj, different evacuation strategies are suggested to control the crowd flow. Mahmood et al. (Mahmood, Haris, and Sarjoughian 2017) presented an optimized agent based real-scale approach, implemented in Anylogic to model and analyze complex crowd behavior, in which different evacuation strategies are analyzed to find out the minimum evacuation time. Another large scale agent-based emergency evacuation model is proposed by Haris, et al (Haris et al. 2019) in Anylogic that ensures the quick and safe evacuation using optimization techniques and route divergence in case of blockage. Harmony search and shortest distance algorithms are used to find out the best evacuation path. Results show that adopting a safety mechanism reduces the overall evacuation time.

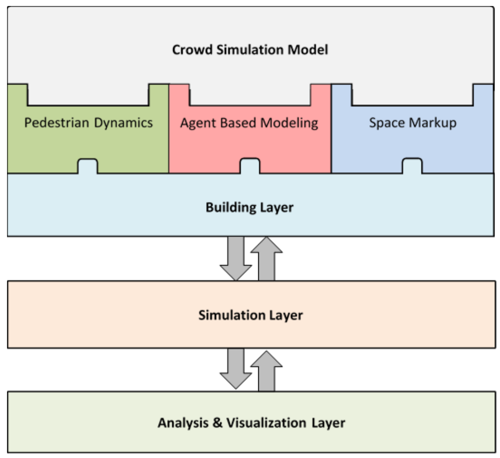

Figure 2: Crowd Simulation & Analysis.

2.2 Pedestrian Dynamics and Crowd Behaviour

Understanding of crowd behavior and the pedestrian dynamics has its application in modeling the evacuation of large buildings and areas. Pedestrian dynamics contribute in the expansion of crowd collective behavior. Tordeux, et al. (Tordeux et al. 2018) simulated pedestrian dynamics at a mesoscopic scale, allowing more granularity and faster simulation of large scale crowds.

Modeling the panic state in agent behavior is more likely to reproduce the real world evacuation process. Wang et al. (Wang et al. 2015) presented a multi agent framework incorporating the individual decision making in a panicked state. Simulation results show that when in panic, agents tend to choose the crowded exits ignoring the alternate pathways. Introducing the role of a virtual leader in agents has shown great improvements in the efficiency of evacuation. The work of (Qiu and Hu 2010) models the grouping phenomenon in pedestrian crowds, and shows that the different group sizes, intragroup structures and inter-group relationships can have significant impacts on crowd behaviors.

Queuing behavior plays an important role in the efficiency of crowd evacuation. Zhou, et al. (Zhou et al. 2019) implemented a cellular automaton model to study pedestrian evacuation based on a real experiment. Focus of queuing behavior in crowd simulation has contribution in reduced pedestrians waiting in queue and shorter evacuation times.

Earthquake evacuation modeling has shown that the distribution of falling debris results in an increase of hurdles in evacuation flow. Lu, et al. (Lu et al. 2019) has applied a social force model for areas of high risk in case of an earthquake. This model is useful in future urban planning. Results show that falling debris affect the evacuation time and the efficiency of an evacuation in a negative way.

3 CROWD SIMULATION & ANALYSIS FRAMEWORK

In this section we discuss our proposed Emergency Evacuation Simulation & Analysis framework, which is capable of: (i) modeling buildings using complex spatial structures and the pedestrians dynamics; (ii) Simulating large crowd flows in the buildings using different scenarios; and (iii) evaluating different evacuation strategies. This helps in creating an adequate evacuation plan or evaluating an existing plan for effectiveness. It is composed of three layers as shown in Figure 2. This layered architecture was initially introduced in (Mahmood, Haris, and Sarjoughian 2017), and is now extended to focus on large scale buildings.

3.1 Building Layer

This layer comprises of three main components: (i) Spatial Environment, (ii) Agent Based Modeling and (iii) Pedestrian Dynamics. The main responsibility of the building layer is to ease the process of modeling complex building structures using CAD drawings and spatial markup tools, and to add walls, doors, passages, obstacles and the exit points in the building. It further allows the modeling of different pedestrian dynamics using agent based approach, such as: Normal/Emergency walk speeds, normal/emergency pedestrian behaviour, choice of exits during evacuation, arcing and clogging at exit points, avoiding obstacles, and choosing safe paths. The modeler can capture the physical environment of the building using CAD Drawings and can incorporate different features in the building using space markup tools, shown in (AnyLogic Space Markup Tools).

The Space markup library within AnyLogic offers the necessary elements required for recreating a scaled graphical model of the spatial environment in which the agents will reside within the model. Its different primitive elements such as, walls, polylines and pathways can help to make floor plans. Next, the modeler can create a logical flow of the pedestrians using the built-in Pedestrian library. The pedestrians are represented as agents with their physical and behavioral characteristics ranging from size (diameter of an average male or female), age, weight, height and gender, normal or handicapped etc. Based on the selected model resolution, the modeler may choose to incorporate these microscopic details in the model given that the tradeoff between the level of details and the execution performance is taken into account. In our proposed model, the pedestrian diameter is taken to be 0.5 meters, using a circular shape to express the approximate area covered by a single pedestrian. We assume the evacuation speed of the pedestrians to be 2.5m/s (OnAverage 2019). A real-scale floor plan of the actual building, developed using the building layer is shown in Figure 3.

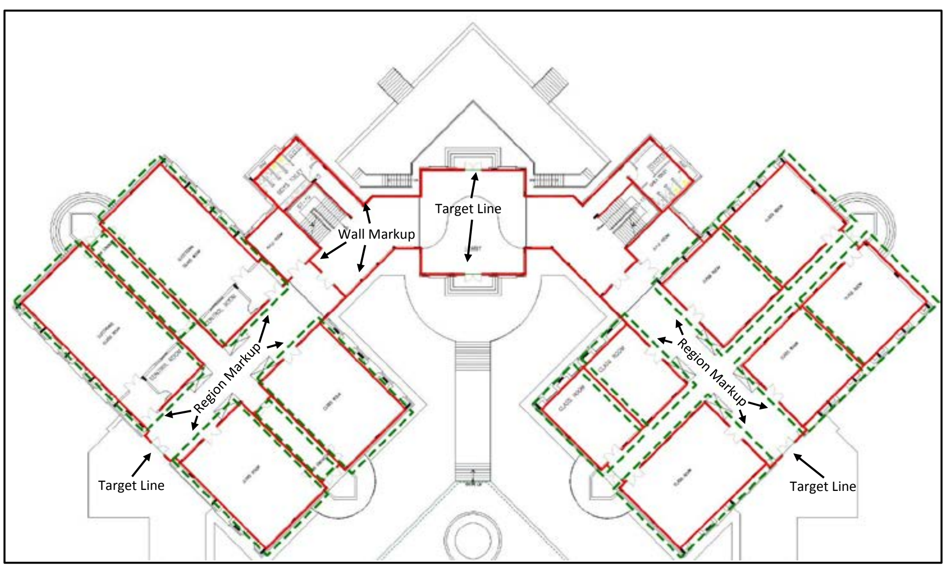

Figure 3: Floor plan of a university building.

3.2 Simulation Layer

The simulation layer couples the building layer with the simulation environment. In this layer the modelers can create different simulation scenarios. It uses crowd simulation techniques to model the different patterns of a crowd and simulate it within the modeled building environment. It allows the modelers to control the flow of the crowd (or selected individuals) and direct the flows towards desired exit paths. It also allows to segregate the crowd into various sub groups and manage their evacuation. Figure 4 shows the pedestrian flow diagram developed in the simulation layer. The symbols used in this figure are explained in (Anylogic Pedestrian Library). For further details the readers are referred to (Mahmood, Haris, and Sarjoughian 2017).

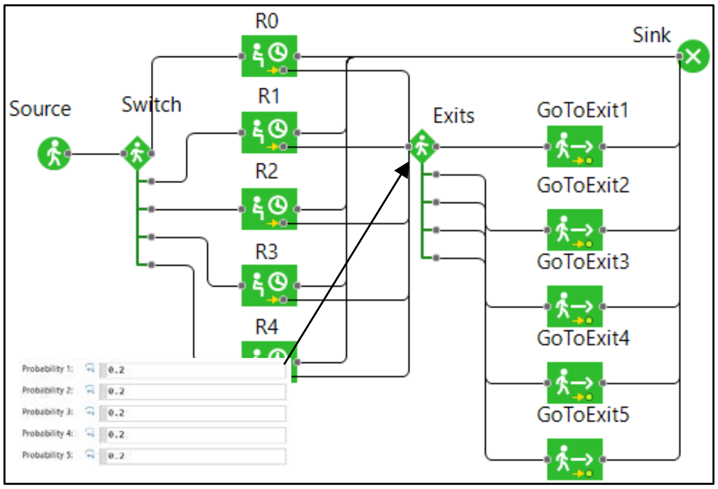

Figure 4: Ped Flow Diagram.

For the sake of simplicity and limited space we only present a single pedestrian source, which is injecting the agents into 5 regions where they wait indefinitely until this activity is cancelled using a 'Cancel-all' event, as shown in Figure 4. This causes all the pedestrians to start evacuating towards five different exit points. The assignment of exits to each pedestrian (or the whole region) depends on the algorithm implemented in the "Exits" switch, which acts as a router and takes the decision of routing a pedestrian or a group of agents towards a suitable exit point. In this example a uniform probability is assigned for a random selection of any exit for all the pedestrians. Later we will discuss how intelligent algorithms can be implemented, that assess the overall situation and make effective decisions.

3.3 Analysis and Visualization Layer

This layer is used to implement and integrate different emergency evacuation strategies and their corresponding optimization algorithms. It further allows the analysis of different evacuation scenarios. This layer interacts with the simulation layer which further interoperates with the building simulation layer to run the model in a loop, using varied parameters, and retrieve back the results to be used as an input for the analysis layer. The analysis framework includes output analysis and visualization. Currently the graphical visualization of the evacuations include time series and moving density charts. These charts are useful to analyze the outputs of different evacuation scenarios and their comparisons.

3.3.1 Emergency Evacuation Strategies

In this section, we present our proposed Emergency Evacuation Technique as an example to model the evacuation strategy, using our proposed algorithm called: *Nearest Exit Shortest Time* (NEST). NEST algorithm focuses on two primary goals. Firstly, the algorithm ensures that all the pedestrians inside the endangered building get access to the nearest exit and secondly, the pedestrians get divided amongst the available exits in such a manner that the chances of arching and clogging at the exits are minimized. This means that pedestrians are directed towards exits assigned to them by the algorithm based on their: (i) region in which they are placed; (ii) distances of these regions from all the possible exits of the building; and (iii) their time window within which they are supposed to evacuate, since not all regions can evacuate parallelly if the number of exits are limited, which otherwise will cause congestions at the exits. Therefore the algorithm will compute a sequence of time windows for each region in order to organize the overall evacuation with minimal overall evacuation time. In our experience time sequence has proved to be better than simultaneous evacuations where congestion causes greater delays.

In order to explain the NEST algorithm, we constructed a simple spatial model consisting of 10 regions, all enclosed within a walled area having 7 exits randomly distributed on the boundary walls. The to-scale dimension of the boundary area is 120’ x 120’ whereas the dimensions of the inner areas range from 13’ x 13’. Figure 5 (a) shows the initial positions of the pedestrians whereas Figure 5 (b) shows the exit assignments computed by the NEST algorithm. It can be seen that all the regions have been assigned T_0 time window whereas R2, R6 and R10 are the three regions which are assigned to Exit1, Exit2 and Exit3 respectively and have T_1 time window.

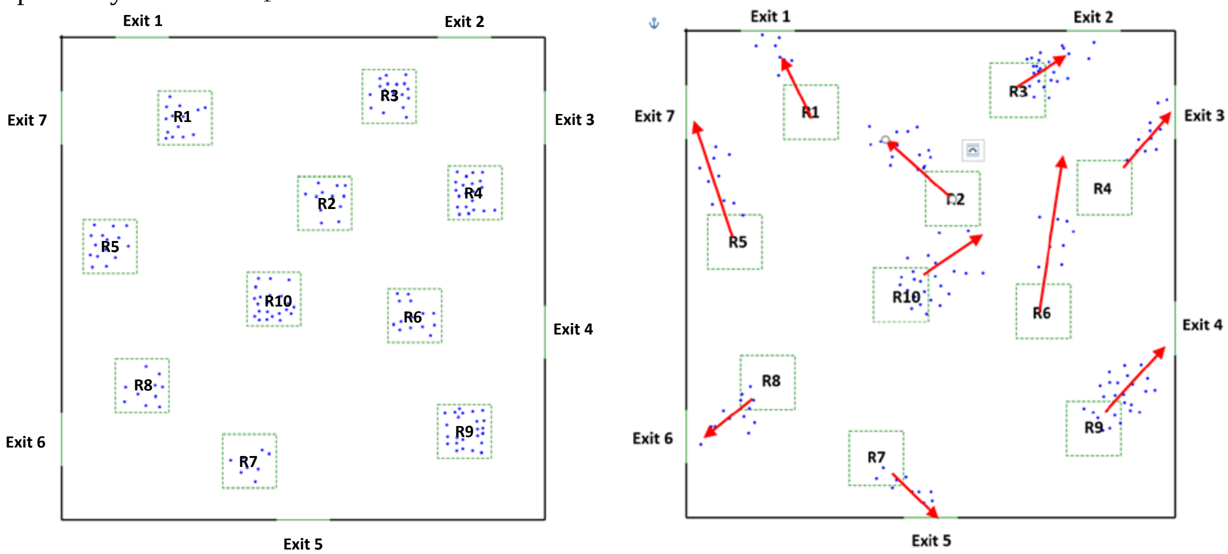

Figure 5: Emergency Evacuation using NEST Algorithm (a) initialization (b) Evacuation.

Algorithm I: NEST Algorithm

Input: Exits[m], Regions[n]
Output: Optimized Matrix

```
1   ⊳ Initialization of Matrix
2   Matrix ← M x N
3   for each Exit i ϵ Exits do
4       for each Region ϵ Regions do
5           Calculate centroid distance of Region from Exit
6       end for
7       Sort distances in ascending order
8   Matrix [i] ← list of all regional distances from Exit i
9   end for
10
11  ⊳ Optimization of Matrix
12  for each Exit j ϵ Exits
13      Select the first occurrence of a region R
14      Remove duplicates from the matrix
15      Perform shift left on the Matrix to fill the gap
16  end for
    ⊳ Matrix optimized
```

Figure 6: NEST Algorithm.

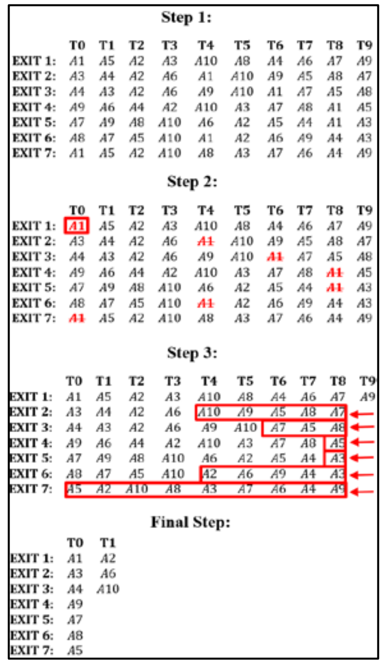

Figure 7: Steps in NEST Algorithm.

Our proposed algorithm is presented in Figure 6. It takes a set of Regions defined in the building layer and the number of available Exits as input. In our above example we have 7 exits and 10 regions. It computes a matrix to output an optimized region-to-exit assignment solution based on different time windows. In line#2, the matrix is initialized. Line#3 - Line#9 initiates an iterative computation of matrix where the regions are placed against each exit in the ascending order of their distances. This sorting order can be replaced with other sorting rules e.g.,, descending order of priority, descending order of safety or shortest job first. Line#12 to Line#16 perform an iterative process of assigning the region to its most suitable exit and the time window.

The details of these steps are illustrated in Figure 7. The final output of this algorithm is an optimized matrix which can be used by the Simulation layer to route the regions towards their assigned exits. The Final output of the algorithm divides the 10 regions into two time windows, T0 and T1 as shown in Figure 7. The regions in the time window T1 will evacuate after the evacuation of the regions in tie window T0 (after a certain delay). This time window mechanism will help in preventing congestion at the exits during evacuation. The final output matrix shown in Figure 7 is applied in the evacuation of the scenario shown in Figure 5 (b).

4 CASE STUDY: CAMPUS EVACUATION

In this section we present the case study of the campus evacuation. After collecting the data from the university administration, we modeled a complete block of the campus building using building layer. Ground floor of the modeled building is shown in Figure 12. The ground floor of the campus building is divided into 15 regions and 10 Exits. The figure shows an initializing of three types of agents: (a) *Red:* Students, (b) *Blue:* Faculty and (c) *Green:* working staff, guards and helpers. The initial positions of each type of agents is as per the proportion of the real entities. The purpose of this distinction of agents is currently to initialize the population as per the collected data, however later it will be used to define the microscopic behaviour of agents. E.g., the green colored staff is more trained in firefighting and rescue and can be modeled as leaders in the leader-follower protocol or can be engaged as first responders and first aid providers. In future we aim to implement the microscopic behavior of different types of agents to address further complexities in the evacuation process. We develop a pedestrian control flow using the simulation layer. We ran three scenarios: (i) With 160 pedestrians, (ii) with 500 pedestrians and (iii) with 1000 pedestrians to evaluate the performance of our algorithm and its comparison with random evacuation. Random evacuation is considered a worst case scenario in any building evacuation because there is no evacuation plan and no predefined exit assignments. Pedestrians in random evaluation are randomly choosing their exits (based on uniform distribution) and may lead to longer paths. Also due to the continuous interruptions of motions, in order to avoid collisions there will be additional delay. We choose this scenario as a lower bound to compare our algorithm. We further validated our evacuation by conducting real experiments. We picked each region shown in the Figure 12 and calculated the approximate time taken to go to the corresponding exit using multiple runs. We used the Pedometer mobile app to calculate the time and calibrate the pedestrian speed. Figure 8 shows the results of the simulation scenario with 160 peds. Figure 9 shows the results of the scenario with 500 peds and Figure 10 shows the results of the scenario with 1000 peds.

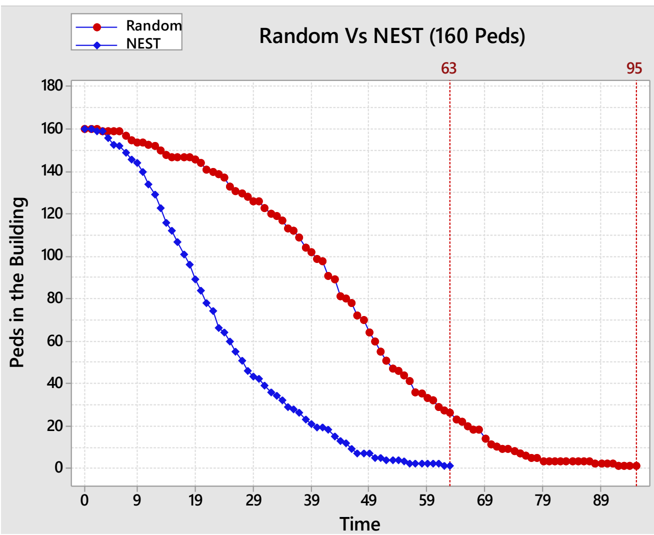

Figure 8: Simulation Scenario 160 Peds. (Time in Secs)

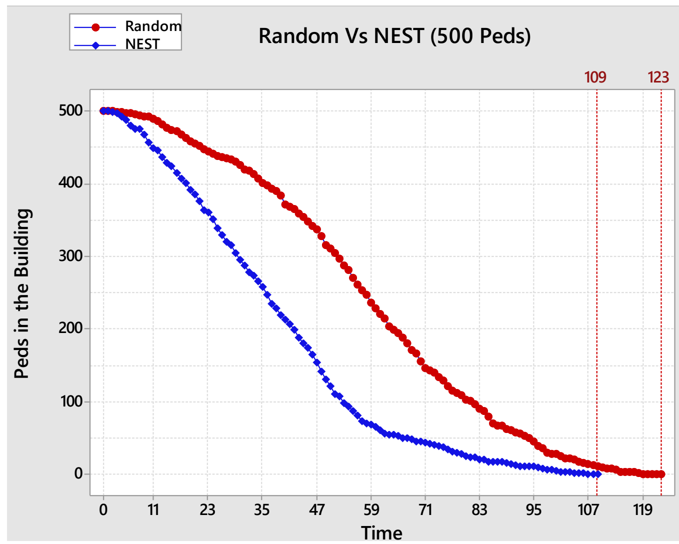

Figure 9: Simulation Scenario 500 Peds. (Time in Secs)

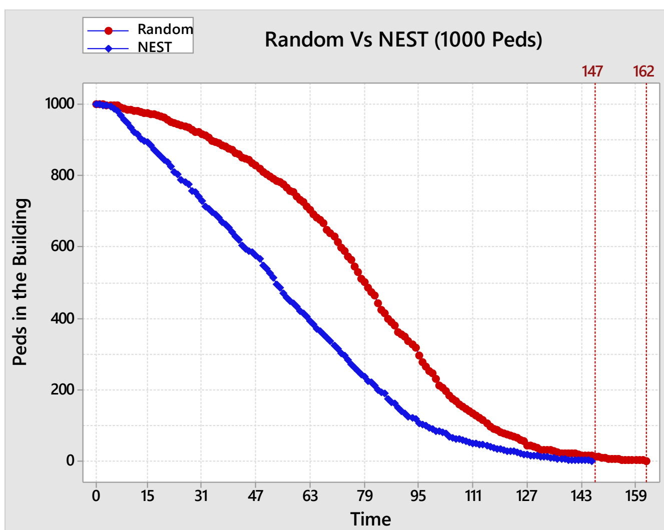

Figure 10: Simulation Scenario 1000 Peds. (Time in Secs)

It can be seen from the results that the NEST algorithm performs better than the random evacuation. It can however be observed that if the population is scaled up even NEST algorithm finds it harder to avoid congestion i.e., the slower descent near the finishing time.

We use the Anylogic University Researcher Edition 8.2.4, (Anylogic 2019a) for the development and the execution of the Crowd Simulation and Analysis framework. The hardware and OS specifications are: DELL OptiPlex 3046 Intel(R) Core(TM) i7-6700 CPU @ 3.40 GHz, RAM: 8GB, Windows 10 Education. The execution times for the NEST algorithm for each scenario are: 63 sec, 109 sec and 146 sec. Whereas the execution times for the Random algorithm for each scenario are: 95 sec, 123 sec and 162 sec respectively.

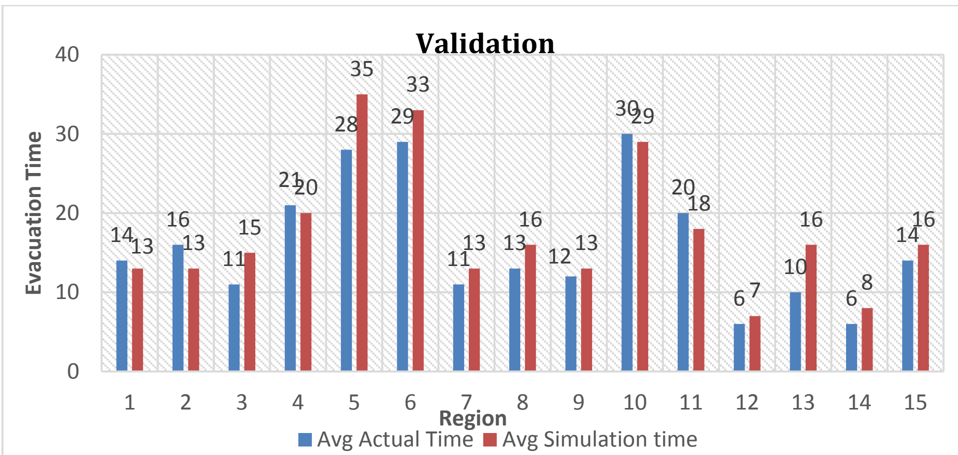

Figure 11: (a) Validation Results (b) Pedometer Mobile App (Time in Secs).

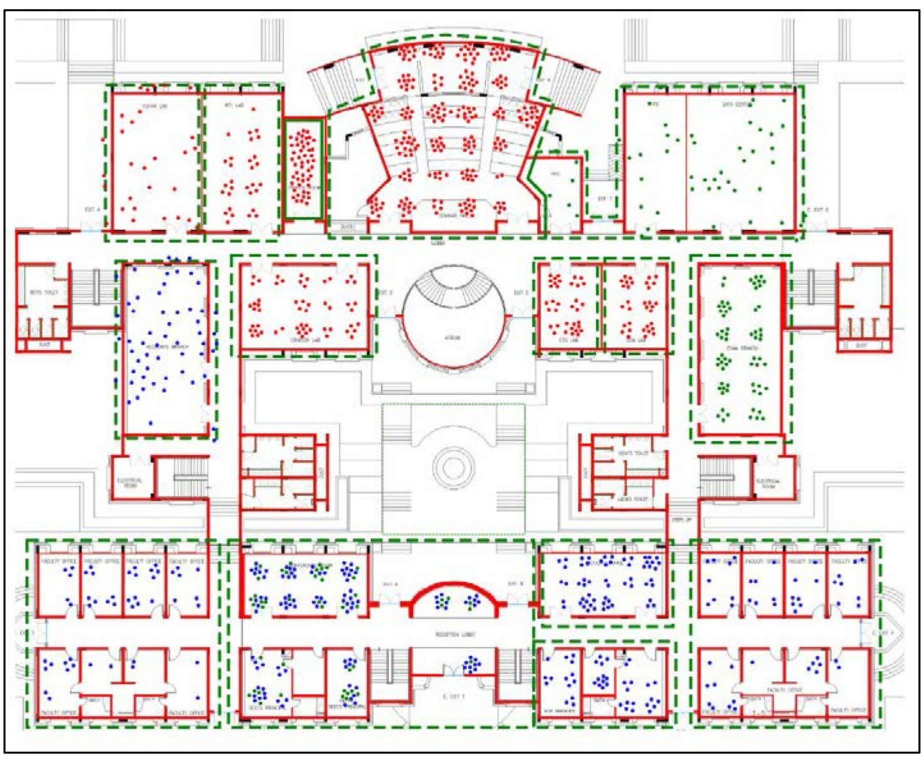

Figure 12: Ground floor of the Campus Building.

SUMMARY AND CONCLUSION

In this paper, we propose a Crowd Simulation and Analysis framework for the emergency evacuation modeling, simulation, visualization, analysis and the optimization of large buildings, using real-scale building structures and agent based approach. We further propose an algorithm called: *Nearest Exit Shortest Time* (NEST), in order to devise an evacuation strategy, that not only assigns exits to different regions based on shortest distances but also load balances the crowd at the different exits by using different time windows. We demonstrate the functionality of our algorithm using a simplistic example and apply the algorithm in a campus evacuation case study using three scenarios. Our algorithm outperforms random evacuation and scales up when the population is increased. The focus of this paper is to propose an evacuation strategy using NEST algorithm and apply it in a real world setting to demonstrate effective building evacuation using crowd simulation framework.

The simulation framework will help develop strategies/policies for effective emergency evacuation plans. It can also be used to analyze existing plans and identify their performance. This research work is in progress. We are developing a mobile app to collect real-time data of pedestrian trajectories which can be used to calibrate real evacuation drills with the simulated evacuation for further validation and assessment.

We aim to implement existing evacuation strategies from the scratch in our crowd simulation framework and compare their performance with our proposed algorithm in future. Our algorithm can further be extended for complex scenarios where priority evacuation is needed, or the exits are to be selected based on safe pathways, in order to avoid paths with fire or blocks. In case of insurgency strikes, the dynamic shift of exit assignments will also be possible. We further plan to use color schemes projected on the floors of the pathways using colored projectors, to guide the pedestrians to follow the paths based on their assigned colors. We further aim to extend the framework to support complex scenarios including fire, earth quakes and insurgency strikes, which require special training, counter measures and effective response management.

REFERENCES

Abdelghany, Ahmed, Hani Mahmassani, Khaled Abdelghany, Hasan Al-Ahmadi, and Wael Alhalabi. 2018. "Incidents in High-Volume Elongated Crowd Facilities: A Simulation-Based Study." *SIMULATION*, September, 0037549718794882.

Anylogic. 2019a. "Anylogic Simulation Platform." 2019. https://www.anylogic.com/, accessed 1st April.

Anylogic. 2019b. "Pedestrian Library Blocks." 2019. https://help.anylogic.com/index.jsp?nav=%2F2_2, accessed 25th August.

Anylogic. 2019c. "Space Markup Palette." 2019. https://help.anylogic.com/index.jsp?topic=%2Fcom.anylogic.help%2Fhtml%2Fui%2FSpace+Markup+palette.html, accessed 25th August.

Chen, D, G S H Tan, A Fagette, and S Chai. 2017. "Simulating Crowd Motion Using Density Estimation and Optical Flow." In , 1169–80.

Christchurch. 2019. "Mass Shooting in Christchurch." 2019. www.edition.cnn.com/2019/03/14/asia/christchurch-mosque-shooting-intl/index.html, accessed 4th April.

Haris, Muhammad, Imran Mahmood, Maryam Badar, Muhammad Saad Qaisar Alvi, Muhammad Saad, and Qaisar Alvi. 2019. "Modeling Safest and Optimal Emergency Evacuation Plan for Large-Scale Pedestrians Environments." In *Proceedings - Winter Simulation Conference*, edited by Imran Mahmood, Maryam Badar, Muhammad Saad, and Qaisar Alvi, 2018-Decem:917–28. Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/WSC.2018.8632418.

Hu, Nan, Jinghui Zhong, Joey Tianyi Zhou, Suiping Zhou, Wentong Cai, and Christopher Monterola. 2018. "Guide Them through: An Automatic Crowd Control Framework Using Multi-Objective Genetic Programming." *Applied Soft Computing* 66 (May): 90–103. https://doi.org/10.1016/j.asoc.2018.01.037.

Jim Burtles. 2016. *Introduction to Emergency Evacuation: Getting Everybody Out When It Counts*. Rothstein Publishing.

Lu, Xinzheng, Zhebiao Yang, Gian Paolo Cimellaro, and Zhen Xu. 2019. "Pedestrian Evacuation Simulation under the Scenario with Earthquake-Induced Falling Debris." In *Safety Science*, 114:61–71. Elsevier B.V.

Mahmood, Imran, Muhammad Haris, and Hessam Sarjoughian. 2017. "Analyzing Emergency Evacuation Strategies for Mass Gatherings Using Crowd Simulation And Analysis Framework." In *Proceedings of the 2017 ACM SIGSIM Conference on Principles of Advanced Discrete Simulation*, 231–40. Association for Computing Machinery. https://doi.org/10.1145/3064911.3064924.

OnAverage. 2019. "Average Running Speed." 2019. https://www.onaverage.co.uk/speed-averages/average-running-speed, accessed 4th April.

Qiu, Fasheng, and Xiaolin Hu. 2010. "Modeling Group Structures in Pedestrian Crowd Simulation." *Simulation Modelling Practice* *and Theory* 18 (2): 190–205.

Tordeux, Antoine, Gregor Lämmel, Flurin S Hänseler, and Bernhard Steffen. 2018. "A Mesoscopic Model for Large-Scale Simulation of Pedestrian Dynamics." *Transportation Research Part C: Emerging Technologies* 93 (August): 128–47.

Vermuyten, Hendrik, Jeroen Beliën, Liesje De Boeck, Genserik Reniers, and Tony Wauters. 2016. "A Review of Optimisation Models for Pedestrian Evacuation and Design Problems." *Safety Science* 87: 167–78. https://doi.org/https://doi.org/10.1016/j.ssci.2016.04.001.

Wagner, Neal, and Vikas Agrawal. 2014. "An Agent-Based Simulation System for Concert Venue Crowd Evacuation Modeling in the Presence of a Fire Disaster." *Expert Systems with Applications* 41 (6): 2807–15. https://doi.org/10.1016/j.eswa.2013.10.013.

Wang, Jinhuan, Lei Zhang, Qiongyu Shi, Peng Yang, and Xiaoming Hu. 2015. "Modeling and Simulating for Congestion Pedestrian Evacuation with Panic." *Physica A: Statistical Mechanics and Its Applications* 428 (June): 396–409. https://doi.org/10.1016/j.physa.2015.01.057.

Zhao, Mingbi, Jinghui Zhong, and Wentong Cai. 2018. "A Role-Dependent Data-Driven Approach for High-Density Crowd Behavior Modeling." *Association for Computing Machinery Transactions on Modeling and Computer Simulation* 28 (4): 1–25. https://doi.org/10.1145/3177776.

Zhou, Di, Jun Hu, Xiaoling Gao, Zhongyu Li, Juan Wei, Mei Li, Bochuan Zhang, and Zhengbin Hu. 2019. "Queueing Behaviors at Exit in Cellular Automaton Model with S-Queue." *International Journal of Modern Physics B* 33 (08): 1950064

AUTHOR BIOGRAPHIES

IMRAN MAHMOOD is currently working as Assistant Professor at the Department of Computing, School of Electrical Engineering and Computer Science, National University of Sciences and Technology, (Pakistan). Imran earned his Masters and doctoral degrees in Computer Systems at the School of Information and Communication Technology (ICT), KTH-Royal Institute of Technology Sweden in 2007 and 2013 respectively. He is serving as the Director of the Center for Research in Modeling and Simulation (CRIMSON). His current research interests are in applied modeling, simulation, analysis and formal verification of complex systems. He can be reached at imran.mahmood@seecs.edu.pk.

TALHA NADEEM is currently pursuing his Masters in Information Technology at the Department of Computing, School of Electrical Engineering and Computer Science, National University of Sciences and Technology (Pakistan). He is serving as a Research Assistant at CRIMSON. His current research interests are Agent based Modeling and Crowd Simulation. He can be reached at tnadeem.msit17seecs@seecs.edu.pk

FAIZA BIBI is currently pursuing her Masters in Computer Science at the Department of Computing, School of Electrical Engineering and Computer Science, National University of Sciences and Technology (Pakistan). She is serving as a Research Assistant at CRIMSON. Her current research interests are Agent based Modeling and Data Analytics. She can be reached at fbibi.mscs17seecs@seecs.edu.pk

XIAOLIN HU Dr. Xiaolin Hu is a full Professor in the Computer Science Department and Director of the Systems Integrated Modeling and Simulation (SIMS) Lab at Georgia State University, USA. He received his Ph.D. degree from the University of Arizona in 2004. His research interests include modeling and simulation theory and application, complex systems science, agent and multi-agent systems, and advanced computing in parallel and cloud environments. His work covers both fundamental research and applications of computer modeling and simulation. He was a National Science Foundation (NSF) CAREER Award receipient. He can be reached at xhu@gsu.edu