VISWALK MICROSIMULATION-BASED EVACUATION MODELING OF A CRITICAL INFRASTRUCTURE: A SOCIAL FORCE MODEL APPROACH

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ABSTRACT

Given the continuous increase in occupancy in critical urban infrastructures, the adoption of evacuation strategies has become a widely recognized solution to tackle the challenges posed by natural or manmade disasters. Unfortunately, even in this modern day and age, Bangladesh has witnessed many disastrous accidents resulting in thousands of casualties due to the absence of effective emergency evacuation plans in high-occupancy infrastructures. Effective development of evacuation plans necessitates the collection of diverse data, encompassing details concerning evacuation duration along with several other factors. In light of this, the primary objective of this study is to establish a methodology to determine the total evacuation time of a 5-storeyed readymade garments factory (RMG), representing a densely populated critical infrastructure. A PTV VISWALK microsimulation model of the study infrastructure was developed to simulate evacuation scenarios to reflect the real-life occupancy data. The Social Force Model (SFM) of pedestrian dynamics has been used to represent the panic amidst people during disaster situations by tuning the walking behavior parameters. Integration of VISWALK and SFM parameters ensures the understanding of pedestrian characteristics and movement, which helps to emulate different types of evacuation scenarios. Machine learning techniques have been incorporated with the Latin Hypercube Sampling (LHS) method in our study to calibrate the parameters for creating emergency conditions to obtain the total evacuation time. Results of the microsimulations show that the minimum total evacuation time (TET) or required safe egress time (RSET) is 8 minutes 7 seconds, exceeding the available safe egress time (ASET) 5 minutes, as found in several fire drill surveys of structure with similar geometries. The findings of this study will enhance the understanding of evacuation dynamics and provide insights into the social force model parameters which can be further utilized in the optimization of emergency response strategies within similar infrastructure. The results showcased in this research will inform stakeholders regarding occupants' safety and provide insights into the potential risks associated with the layout of analogous structures, thereby ensuring more resilient urban environments.

Keywords: *Disaster, Emergency Evacuation, Critical Infrastructure, Simulation, PTV VISWALK*

1. INTRODUCTION

The implementation of mass evacuation strategies in critical infrastructure, focusing on saving maximum lives and ensuring minimal casualties, is a challenging task in any emergency. Inadequate and unstructured evacuation planning policies make the situation more difficult and critical while pushing occupants into high-risk and vulnerable conditions. Occupational safety and health are closely related to this, and over the decades, they have been highly compromised within the historical context of Bangladesh. The country has witnessed several tragic and fatal incidents over the years, such as structural collapses of buildings and fire incidents, where industrial buildings of ready-made garments (RMG) were the main sufferers, resulting in 1500 deaths and hundreds of casualties (Brown, 2015). The most highlighted catastrophes include fire incidents at the Tazreen Fashions Garments factory in 2012 (Manik & Yardley, 2012) and the collapse of the Rana Plaza Garments factory in 2013, which resulted in 1132 deaths and more than 2500 injuries (Trebilcock, 2020). Along with human-caused disasters, Bangladesh is highly vulnerable to natural disasters such as earthquakes, owing to its geographical conditions and land characteristics. However, the investigation reports ensured that preparedness, drill practices, robust monitoring, and heightened owner awareness could have minimized losses; therefore, risk assessment and evacuation planning are of utmost importance.

To address this issue, there is an urgent need to evaluate the safety performance of critical infrastructures to ensure the safety standard. The RMG industry is deemed to consist of critical infrastructures of Bangladesh because of its high occupancy and complex operational environment. The presence of a large workforce in manufacturing facilities poses unique challenges during emergencies, making it essential to meticulously assess evacuation strategies. To perform a safety evaluation, occupant evacuation modeling is a practical approach that enables the demonstration of a possible real-life disaster.

Numerical experiments using an evacuation modeling tool overcome the challenges and disadvantages of traditional experiments (Johansson, 2014). A handful of studies have also been conducted with numerical methods addressing pedestrian evacuation time, evacuation efficiency, identifying bottlenecks in the evacuation process, and providing evacuation guideline strategies. Dong *et al*. (2015) experimented with numerical analysis in the event of a fire in a supermarket and calculated the required safe evacuation time based on which safety requirement scheme could be proposed. In another study, Zhao and Gao (2010) focused on the exit-choice behavior of pedestrians and their effect on evacuation efficiency. Liu *et al.* (2009), employed a modified Cellular Automata (CA) model to simulate evacuation scenarios in the classroom, whereas Li *et al.* (2015) experimented to study the panic scenario of a classroom evacuation utilizing the social force model (SFM) based on a real-life earthquake event. Kretz *et al*. (2008), and Marten and Henningsson (2014) focused on portraying pedestrian flow through bottlenecks and identified the influence of the parameters of the simulation tool on the characteristic behavior of pedestrians using the social force model (SFM) and VISWALK as the simulation environment.

In the context of Bangladesh, Saha *et al*. (2019) studied the required evacuation time under two different scenarios to check the evacuation efficiency in a 5-storeyed typical pharmaceutical cleanroom in the event of a fire accident using evacuation modeling with Pathfinder. In another study (Khandoker *et al.*, 2018), a similar kind of research was revised where the simulation of a 7-storeyed ready-made garments (RMG) factory building was considered using Pyrosim software for risk assessment and tenability effect analysis. R.M. Khan *et al.* (2021) carried out evacuation experiments and simulations in a ready-made garments factory under a fire scenario as a safety assessment. The study results show a higher evacuation time in the case of open fire doors, obstacles in the egress routes, and a reduced number of exits.

The aforementioned studies could limitedly focus on the optimization of parameters for the simulation of pedestrian evacuation. Moreover, from the perspective of the critical infrastructure in Bangladesh, researchers have only highlighted the fire protection design of buildings and their appropriateness. Notably, there is a shortfall in the literature elucidating the fixed methodology to assess the detailed evacuation process in the case of any emergency. To address these knowledge gaps, an attempt has been made in this paper to develop a robust pedestrian evacuation simulation model of a critical infrastructure, considering a 5 storeyed readymade garments factory as a representative of this category of structures, in the VISWALK platform with the utilization of Social Force Model (SFM). This simulation software is an add-on module of VISSIM that has been gaining acceptance because of its appropriate application in numerous domains such as evacuation modeling, urban planning, safety analysis, and traffic management (Hoque & Naz, 2023). Among various pedestrian models, likewise, the Cellular Automata (CA) model, Agent-Based Model (ABM), Social Force Model (SFM), etc., the last better imitates specific pedestrian features such as individual intelligence in decision-making by avoiding forces during evacuation (Ibrahim & Hasan, 2023). Because of that, the integration of the SFM and VISWALK parameters in the developing model ensures a better understanding of pedestrian characteristics and captures the key features of pedestrian movement. Therefore, this study utilizes this model and simulation tool for testing and evaluating evacuation scenarios considering occupant behavior and interactions and aims to provide a set of calibrated parameters under emergency conditions. In addition, considering the average speed and total evacuation time as two fundamental keys to investigating evacuation efficiency, a sensitivity analysis was performed to observe the influential parameters on average speed during the evacuation procedure.

2. METHODOLOGY

The progress of this paper has been organized in a meticulous way to understand the intricate relationships existing in the walking behavior parameters of the social force model. The framework of this study is explained through a flowchart as showcased in Figure 1.

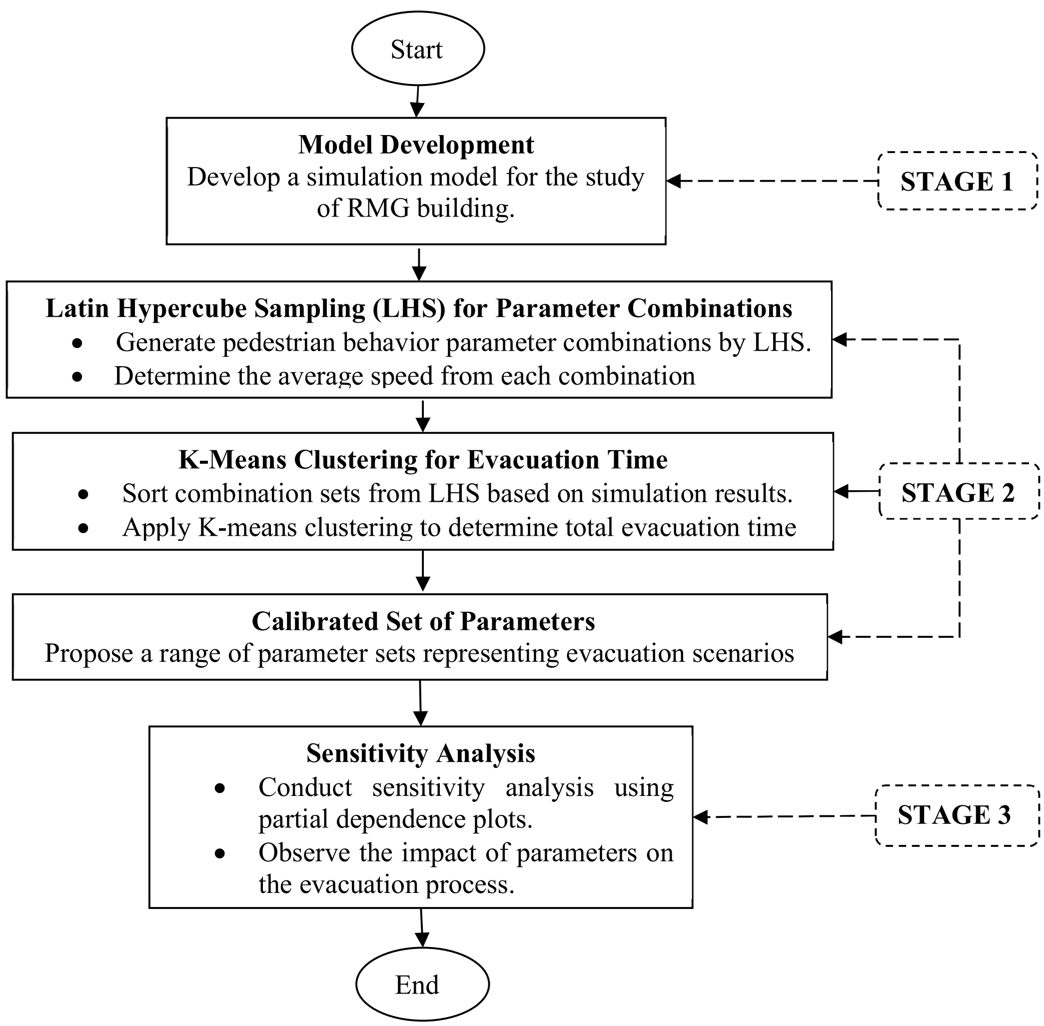
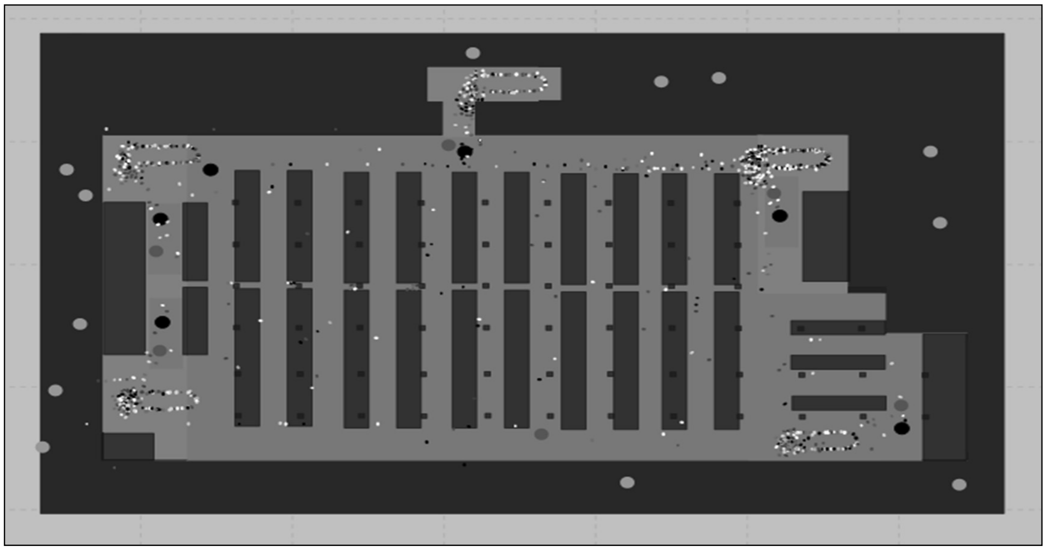


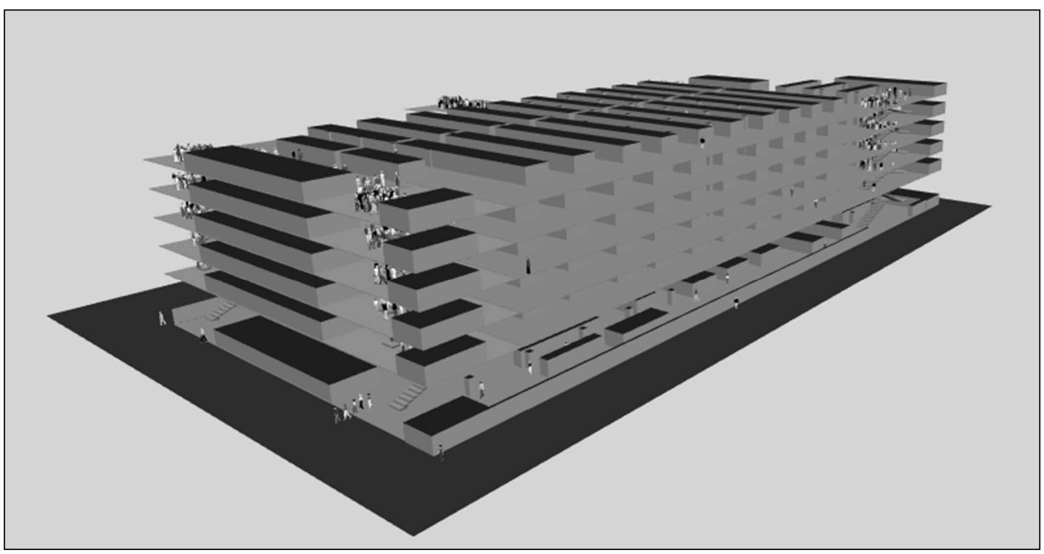
Figure 1: Overall framework of research methodology

2.1 Simulation model development

To replicate the realistic environment and evaluate the emergency scenario, VISWALK simulation model (Figure 2) is created for the RMG factory. Necessary components are generated in the model along with 1000 pedestrians as the considered RMG factory was designed for around this number of occupants including all the staff and workers in total. Only stairs are considered as an escape route as lifts are shut down or highly risky to use in any kind of disaster, such as a fire incident or earthquake. All machineries have been added as blockages as they are considered as obstacles for the evacuees.



(a)



(b)

Figure 2: Visual observation of pedestrian movement in VISWALK (a) 2D view (b) 3D view

2.2 Calibration of the simulated model

Introducing the concept of the social force model (SFM), Helbing and Molar (1995) suggested that pedestrian motion is guided by social forces that are responsible for changes in pedestrian behavior. The attractive and repulsive effects of pedestrians walking in the same direction represent this social force. Realistically and reliably, stochastic pedestrian walking behavior can be reproduced by SFM parameters. Social, psychological, and physical forces are considered in this model, which arise from the pedestrian's desire to reach the destination, the influence of other pedestrians, and surrounding obstacles in the environment. The social force model was expanded along with the integration of VISWALK parameters by Dr. Helbing (PTV Manual, 2021).

The pedestrian behavior in this particular simulation model includes integrated parameters of SFM and VISWALK, in the range of default values presented in Table 1, representing the behavior of pedestrians realistically and reliably. Microsimulation modeling with default values can produce unreliable results that likely deviate from the actual results (Marten & Henningsson, 2014).

Table 1: Description and standard range of SFM Parameters (PTV Manual, 2021)

No	Parameters	Description	Usual Range
1	Tau (τ)	Represents the relaxation time of pedestrians.	0–1
2	Lambda (λ)	Assesses the behavior of individuals behind someone.	0–1
3	React to N	During the overall force calculation for a pedestrian, only the impact generated by the nearest n pedestrians is taken into account	≥ 0
4	Noise	The greater this parameter value, the more potent the random force adds to the systematically calculated forces.	0-2
5	VD	Defines response of individual to group in counter flow.	≥ 0
6	ASocIso	Regulates the social force between two pedestrians.	2.72
7	BSocIso	Captures the randomness of pedestrian movements in force calculations	0.2
8	ASocMean	Governs the strength of the social force between two pedestrians	
9	BSocMean	Governs the range of the social force between two pedestrians	

To overcome these drawbacks, the simulated model must be calibrated before implementation. To conduct the calibration, an innovative approach has been taken by incorporating Latin Hypercube Sampling (LHS) and K-means clustering. A large number of sets of parameters within a specific range have been generated using LHS and the model is simulated for each combination to find the average speed. In the 2nd phase of calibration, a combination of sets of parameters with evacuation speed are clustered by the K-means algorithm, based on which simulation is conducted again, and the average travel time is identified.

2.2.1 Walking Behavior Parameters Sampling

One of the most effective sampling techniques is Latin Hypercube Sampling (LHS), which is a stratified sampling procedure that deals with the variables of multivariate distributions to provide an efficient way of sampling variables. Good coverage of each uncertain parameter space is ensured using Latin Hypercube Sampling (McKay, 2000). The non-repetition of sampling in LHS is maintained thoroughly, which means that random samples are selected one at a time by taking into account the previously generated samples, which makes those samples representative of the real variability.
Incorporating the concept of "Latin Square," in two-dimensional statistical sampling, the sample size of N of each of the two variables is partitioned along each dimension into N disjoint intervals with an equal marginal probability of 1/N in a square grid in such a way that each row and column contains only one sample (Sheikholeslami & Razavi, 2017). In multidimensional sampling, the Latin Hypercube is the generalized form, where each hypercube contains only one sample in each axial dimension.

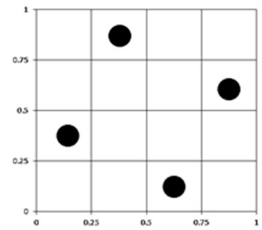
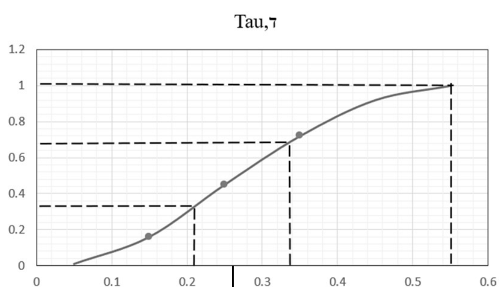


Figure 3: Fundamental concept of LHS A 2-dimensional sampling of 4 samples

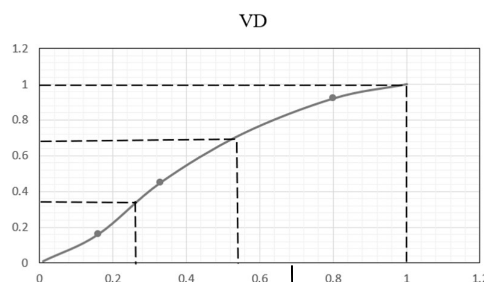
The general process of Latin Hypercube sampling to create the combinations is visually represented in Figure 4 and is summarized below:

- The cumulative distribution function is plotted for each parameter for a certain parameter range.
- The cumulative distribution plots are stratified equiprobably into the number of required samples. For example, plots are divided into *N* equal intervals for *N* number of samples.
- For each variable, a random sample is drawn from each stratum and actual values of those samples are extracted from the cumulative distribution curves.
- The obtained samples from each variable are paired or combined randomly to create different sets of parameters.

In this study, a total of 200 combination sets of walking behavior parameters are generated using Python to reduce the computational time.



Probability	Actual Value
.33	0.21
.66	0.34
.99	0.55



Probability	Actual Value
.33	0.23
.66	0.47
.99	1

Combination of parameters set

Tau	VD
0.21	0.23
0.21	0.47
.34	0.23
.	.
.	.
0.55	0.47
0.55	1

Figure 4: Process of Latin Hypercube Sampling

2.2.2 Generation of a range of set of parameters

As evacuation behaviour is required in this particular study, the simulations with only evacuation speeds are chosen out of those 200 simulations obtained through LHS. A range of each parameter is found for the emergency speeds which leads to the necessity of narrowing down the range of the parameters in the most reliable way. The clustering algorithm emerges to be an effective way in this case.

Clustering, an unsupervised machine learning method, is one of the most efficient methods in dividing and grouping the data points with similarity and dependency to other data points in the same group. Among several clustering methods, the K-means algorithm appears as a fast and simple technique with very good clustering results. Focusing on reducing the variance among the data sets within the same group or cluster, this is a partitioning and centroid-based algorithm that groups the data points into k different clusters through the iteration process until convergence to a local minimum is obtained (Na *et al.*, 2010). At the very first stage, k fixed centers of k clusters are selected randomly and each data object is assigned to one of the nearest clusters employing a distance metric such as Euclidean distance. After initial clustering, recalculation of cluster centroids is performed by taking the mean of all data points in the same group, and the clustering process is iterated again, continuing until the change of cluster centroids is insignificant.

In this study, the number of target clusters is 5 and the process of the K-means algorithm is shown in Figure 5.

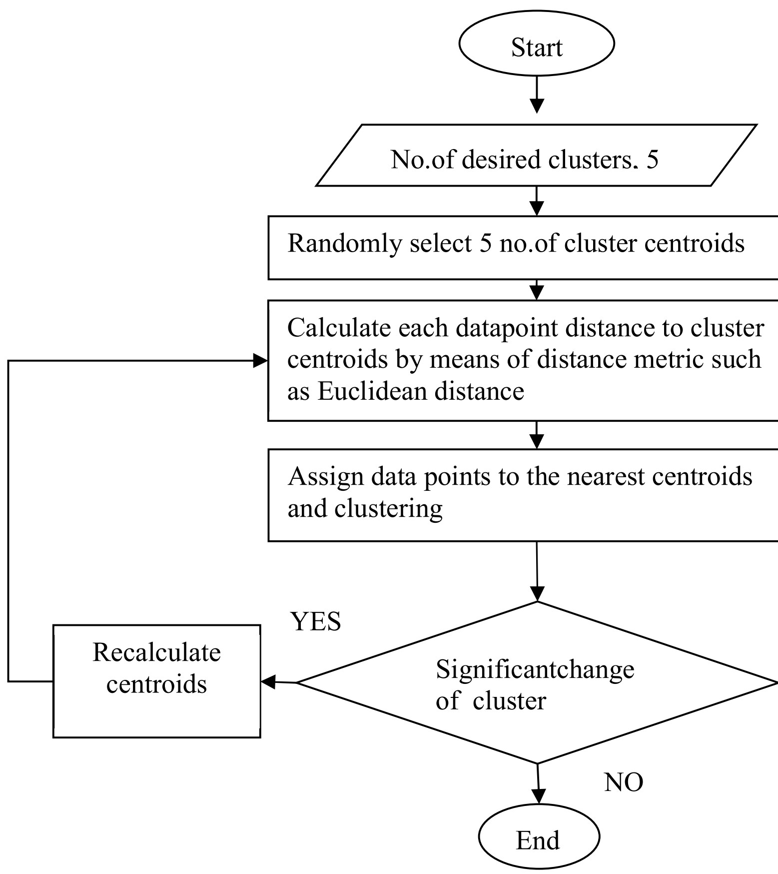


Figure 5: Flowchart of K-means clustering algorithm

3. RESULTS

3.1 Analysis of Model Simulation

Latin Hypercube Sampling (LHS) has been utilized for sampling and a combination of parameters that are already discussed in section 3.2.1. 200 combination sets of parameters have been generated by the LHS algorithm and simulation has been conducted 200 times resulting in several scenarios for each parameter set. One of the key parameters to evaluate evacuation efficiency, the pedestrian average speed, has been found for each simulation. The variation in average speed could be observed, with lower speeds replicating the normal conditions while high speeds replicate the emergency scenarios. The average speed value of 3 km/hr has been suggested in the literature (Alam *et al.*, 2023) to be the evacuation speed. Thus, for this study, walking parameters set having average speeds of more than 3 km/hr have been kept for further analysis (Table 2) to identify the total evacuation time.

Table 2: Selected combination of parameter sets for K-means clustering

Para-meters	**Tau (τ)**	**Reac-Ton**	**ASoc-Iso**	**BSoc-Iso**	**Lamda (λ)**	**ASoc-Mean**	**BSoc-Mean**	**VD**	**Noise**	**Avg. Speed**
Range	0-1	0-10	0-10	0-10	0-1	0-10	0-10	0-10	0-10	
	4.512	6	4.631	7.766	0.779	6.854	5.811	8.279	9.347	3.001
	5.022	10	2.737	7.828	0.536	5.719	5.001	3.18	7.77	3.029
	6.301	3	9.283	8.295	0.713	1.625	6.889	6.942	7.923	3.039
	7.52	5	8.603	3.148	0.556	5.198	4.83	3.508	7.022	3.053
	5.556	10	3.704	9.47	0.395	3.155	8.951	4.321	7.184	3.059
	5.671	5	2.348	1.509	0.454	2.642	1.192	7.46	7.718	3.089
	8.317	8	9.419	5.164	0.661	6.344	9.541	9.954	7.059	3.094
	5.331	9	4.002	8.058	0.286	5.364	3.539	1.705	9.377	3.105
	5.616	10	5.224	5.094	0.503	0.071	7.112	1.845	9.472	3.108
	6.397	7	9.221	7.6	0.51	5.572	7.282	9.142	9.29	3.127
	4.758	2	1.841	3.686	0.614	8.305	5.942	6.775	8.561	3.128
	9.774	7	5.675	5.362	0.878	6.583	1.834	7.037	6.957	3.129
	5.766	2	4.11	7.12	0.086	8.758	6.152	2.512	9.85	3.132
	9.028	10	6.043	4.56	0.583	0.643	2.362	3.101	7.33	3.132
	7.239	1	8.084	8.59	0.948	5.406	6.328	7.71	7.851	3.135
	8.356	1	7.448	1.845	0.594	4.576	2.559	0.685	9.69	3.143
	6.582	6	2.951	7.153	0.097	6.646	0.057	1.475	8.763	3.149
	7.881	6	5.87	7.268	0.25	1.39	0.513	0.594	8.149	3.155
	5.444	4	7.694	1.905	0.859	5.919	3.876	9.946	8.88	3.162
	5.535	7	6.082	8.634	0.427	7.31	7.757	9.513	8.534	3.169
	6.143	4	5.475	4.378	0.442	8.944	5.864	3.663	9.958	3.172
	9.349	5	4.815	1.72	0.297	4.605	8.534	5.482	7.994	3.173
	6.735	5	2.394	5.326	0.494	6.906	1.448	4.675	7.802	3.175
	9.91	6	5.444	3.566	0.847	1.596	7.029	8.128	9.862	3.183
	7.754	7	0.48	8.934	0.009	3.913	5.996	3.822	9.125	3.187
	6.885	8	0.426	5.873	0.259	0.657	0.284	6.308	9.568	3.187
	8.734	9	7.126	7.674	0.051	3.498	2.175	8.719	8.995	3.189
	9.055	10	3.446	9.817	0.87	3.734	0.687	3.998	8.929	3.21
	9.595	8	0.749	6.431	0.367	2.072	1.728	5.117	8.651	3.212
	7.685	10	5.828	4.733	0.2	4.855	2.606	9.795	9.048	3.229
	5.86	2	1.222	5.476	0.469	7.388	8.372	9.008	9.633	3.252
	7.453	1	5.589	5.963	0.141	9.718	1.083	4.046	8.635	3.256
	8.2	3	2.212	1.07	0.795	6.983	4.7	4.185	8.422	3.267
	9.183	3	4.852	5.76	0.609	7.845	5.325	8.854	8.287	3.354

3.2 Proposed sets of parameters

The evacuation efficiency and safety evaluation are analyzed based on the Available Safe Egress Time (ASET) and the Required Safe Egress Time (RSET). The Available Safe Egress Time (ASET) is the duration between the initiation of an emergency and the point at which conditions become unsustainable. On the other hand, the Required Safe Egress Time (RSET) denotes the time required for the last occupant to exit the building. Out of 200, 34 simulations having pedestrian speeds more than 3 km/hr have been further incorporated into the model to find the total evacuation time. To understand the range of each parameter in-depth for emergencies, the parameters of sorted simulations have been conducted through K-means, and from the clustering results, five groups have been extracted as clusters because more than five do not exhibit explicit differences among the parameters. The total evacuation time of each simulation is represented in Table 4 where the highest and lowest values of each parameter can define the range of a set of parameters for 1000 occupants. Table 4 represents the proposed calibrated set of parameters for evacuation scenarios under emergency conditions.

Table 3: Sets of parameters for 5 emergency scenarios

Tau (τ)	React To N	ASoc-Iso	BSoc-Iso	Lamda (λ)	ASoc-Mean	BSoc-Mean	VD	Noise	Avg Speed	TET
6.839	3	4.661	5.298	0.309	7.591	2.861	2.843	9.116	3.171	8 min15 sec
6.064	9	3.353	7.889	0.298	3.126	6.4	2.923	8.79	3.118	8 min 22 sec
8.579	8	4.395	6.465	0.432	2.929	1.524	5.584	8.453	3.188	8 min 7 sec
7.322	4	4.337	3.093	0.611	5.609	5.533	7.038	8.487	3.184	8 min 9 sec
6.758	5	8.418	7.657	0.652	5.251	7.559	8.652	8.131	3.113	8 min 26 sec

Table 4: Range of sets of parameters for simulation to determine the evacuation time

Tau (τ)	Reac-ToN	ASocIso	BSocIso	Lamda (λ)	ASoc-Mean	BSoc-Mean	VD	Noise
6.064-8.579	3-9	3.353-8.418	3.093-7.889	0.298-0.652	2.929-7.591	1.524-7.559	2.861-8.652	8.131-9.116

The total evacuation times observed under each emergency condition, demonstrate that the minimum required evacuation time is 8 minutes and 7 seconds to evacuate the occupants safely.
From the analysis and data of fire drills conducted at several RMG factories, having similar geometry to this study model, the required evacuation time is 5 minutes (Khan et al., 2021). This can be considered as the available safe egress time (ASET) for the safe evacuation of occupants. However, the total evacuation time (TET) or RSET obtained from this study surpasses the ASET representing the fact that the existing building is not capable of safe evacuation possessing a significant risk of injury to occupants.

3.3 Sensitivity Analysis

In this study, only individual effects of the parameters on average speed are evaluated from 200 simulation runs, which means the relationship between one feature with the average pedestrian speed is analyzed, while keeping other features or parameters constant. From the illustration of the partial dependence plots (PDP), influences of parameters such as relaxation time, tau (τ) (Figure 6(a)), lambda (λ) (Figure 6(b)), individual response to grouped people (VD) (Figure 6(c)), etc. are observed on pedestrian speed i.e., pedestrian movements activity. While the increase in pedestrian speed suggests panic situations amidst people, a decrease in speed indicates that the pedestrians are in no emergency condition or emergency condition with long queued lines. Other parameters in, including React to N, Noise, ASocIso, BSocIso, and ASocMean (Figure 6(d)-(h) respectively) have also been found to be influential but no evident correlation has been found for BSocMean (Figure 6(i)).

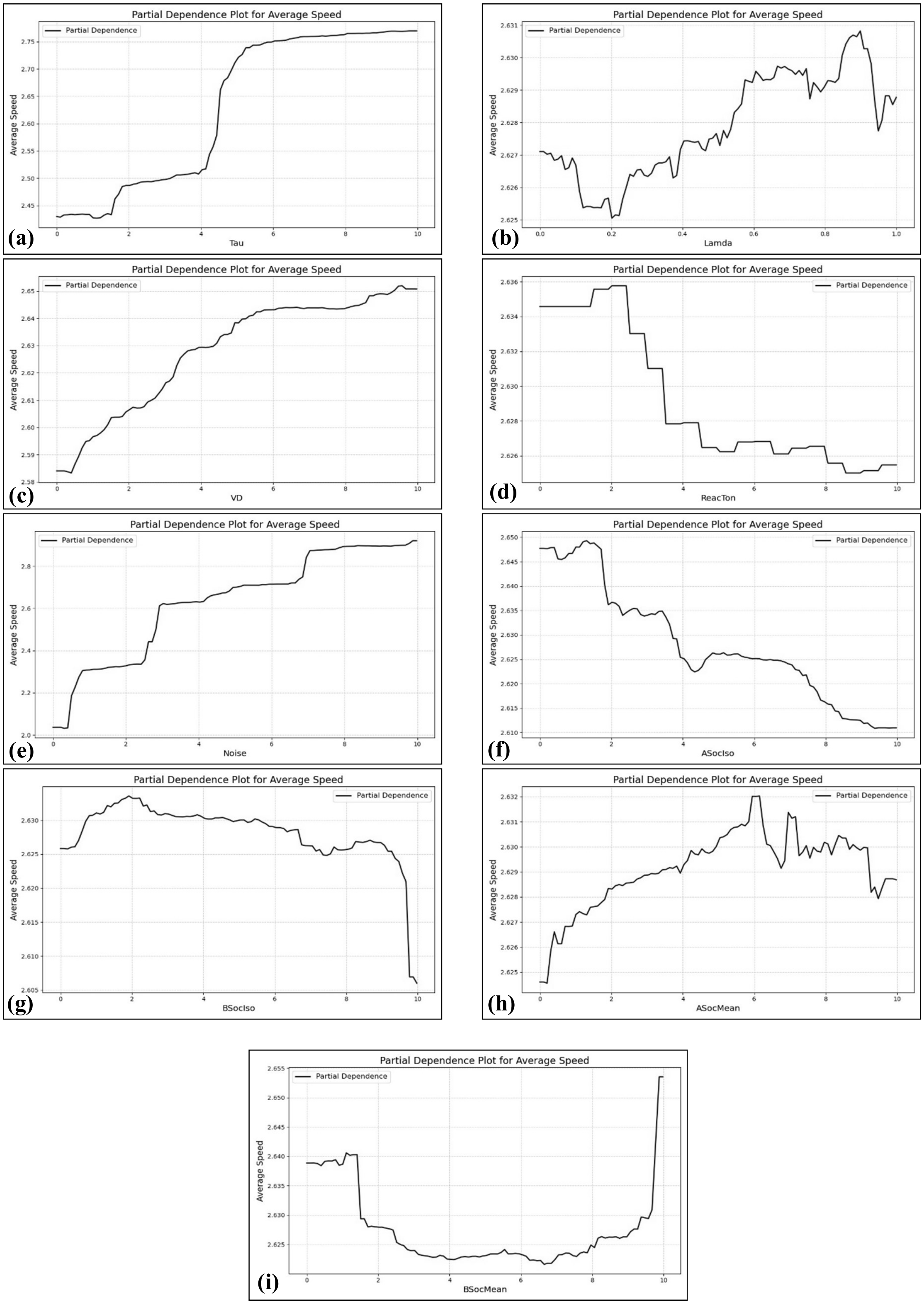


Figure 6: Partial dependence plots (PDP) for average speeds of parameters (a)Tau, (b)Lambda, (c)VD, (d)React To N, (e)Noise, (f)ASocIso, (g)BSocIso, (h)ASocMean, and (i)BSocMean

3.4 Discussion

This research has attempted to establish a methodology, proposing parameter set values to identify the required evacuation time of any large critical structure, such as multi-storeyed buildings by adopting advanced reliable techniques. The proposed calibrated set of parameters will be a benchmark for future works to determine evacuation time for any similar infrastructure in emergency conditions, which no other previous research has provided yet in the context of Bangladesh. Moreover, the sensitivity analysis of the walking behavior parameters provides insight into pedestrian movements in the simulation. This helps to understand the parameters' influence and dependency on the movement speed of pedestrians. If the results of the methodology adopted in this paper fall short for other pedestrian evacuation scenarios, the sensitivity analysis can be used as a guideline to recalibrate the VISWALK model. The relationship between the parameter and the average speed of pedestrians can be understood by following the trendlines. Thus, these plots have the potential to serve as a framework for future similar research.

However, the total evacuation time from this study exceeded the available safe evacuation time and raised questions about the design safety and safety assessment of the existing structure. It also imposes the necessity of calculating the evacuation time and evaluating evacuation capabilities during the design phase before constructing any structure. To improve the condition of the existing structures with insufficient TET or RSET, several effective measures can be adopted. Khan et al. (2021) suggested improving the egress path by increasing the number of exits, widening the existing doors, and eliminating the obstacles in the environment. Along with that, some additional steps can also be considered, such as, ensuring that the number of occupants is safe enough for evacuation by providing more community spaces and maintaining working hour shifts to limit the occupant capacity at a time.

4. CONCLUSIONS

The evaluation of the evacuation process of critical infrastructure holds crucial importance to ensure the safety of a large number of people and save lives. In recognition of the research gap in an established methodology to find evacuation time, and evacuation efficiency for multi-storeyed buildings in the perspective of Bangladesh, this study has outlined an experimental simulation with the SFM model in the VISWALK platform. A 5-storeyed readymade garments factory, with an occupant number of 1000, has been chosen for the microsimulation modeling to formulate a methodology and assess the evacuation time. The suggested approach of the formulation was implemented by incorporating Latin Hypercube Sampling and machine learning techniques in several stages. The findings of this paper give insight into the following topics:

- A range of sets of calibrated parameters to find total evacuation time.
- The minimum total evacuation time (TET) or required safe egress time (RSET) is more than the available safe egress time (ASET), indicating the high possibility of a huge number of people being trapped in the building along with a huge risk of casualties.
- Partial dependence plots (PDP) for sensitivity analysis to have insight into the effects of parameters on pedestrian average speed.

These findings demonstrate the necessity of incorporating soft and hard strategies like revised building design and evacuation policy standards. Although this research poses limitations such as not addressing the detailed findings on possible bottlenecks and not identifying points of risk in the structure, the model is flexible enough to consider these and to adopt any required changes. This modeling framework contributes to finding out the evacuation time and efficiency of structures that can be utilized in improving evacuation procedures and safety measures in RMG or any large densely populated infrastructures in Bangladesh.

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