

Optimization of Egress Controls of Fire Emergency Management Plans using Agent based Simulation: A Case Study of Ready-made Garment Industry

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Abstract: Ensuring a profound occupational health and safety in Readymade garment industries is a challenge for the developing countries despite having significant painstaking efforts. Recent statistics show that, the workers of this sector are in vulnerable conditions due to their exposure to fire risk at the factories and this risk gets worse during an emergency due to bottlenecks of egress components and clogging. Therefore, the emergency management plans of the RMG sectors needs to be optimized for safety of workers. The research work of this paper analyzes and explores the way of addressing underperforming emergency plans by optimizing evacuation strategies. For this purpose, an RMG factory in Bangladesh is selected as a case study. Based on the data provided by the factory management and survey regarding occupant's perception, a simulation model in an evacuation simulation is built. Fire risks at the factory are analyzed through risk analysis tools for worst case scenario to assess the existing risks. The results reveal that the application of risk analysis tools along with an agent-based evacuation can benefit the entire RMG industry by reducing the risks of bottlenecks and clogging of egress controls that endangers lives of workers, thereby in optimizing the efficacy of fire emergency management plans.

1 INTRODUCTION

The Apparel industry, also known as Readymade Garment (RMG), of Bangladesh is making vital contribution to the emerging economy as well as acting as the major catalyst of the development of the country. The readymade garment sector is accounted for 81 percent of the total export earnings and is the single biggest export earner for the country with about four million workers (Hasan, M. and Mahmud, A., 2017).

Being a developing nation, Bangladesh government as well as the employers has not paid much attention to ensure workplace safety in the RMG industry (Barua, U. and Ansary, M.A., 2017). As a result, this sector has continuously been facing tragic incidents one after another. According to the Centre for Policy Dialogue (CPD), a well-known research organization working with the occupational health and safety in Bangladesh, 161 safety incidents

have taken place in the RMG sector resulting 3875 injuries and 1303 deaths from November 2012 to March 2018 (Solidarity Centre, 2018).

The Tazreen Fashion fire in 2012, one of the tragic incidents in the Bangladesh apparel industry, in 2012 that caused about 112 dead and more than 200 injuries followed by the Rana Plaza collapse in 2013 resulting 1134 dead and 2500 injuries awoke the whole country as well as the world to the poor working conditions in the Readymade Garment industry of Bangladesh (Barua, U. and Ansary, M.A., 2017). The government as well as other stakeholders like the ILO, the Accord, the Alliance etc. have taken various initiatives to make the workplace safe.

This research paper has put emphasis on the implementation of the operational emergency management principles using risk analysis tools and simulation of an evacuation model with worst fire scenario to make proper emergency management strategies and proper recommendations for the

selected factory building as well as for the RMG industry in Bangladesh.

2 OBJECTIVES

The aim of the study is to find out an effective solution of reducing the exposure of risks to workers in case of fire evacuation in RMG factories in Bangladesh. This paper tries to analyze the anticipated potential fire scenarios based on ISO 16733-1 and how the Pathfinder simulation software can help assess the risk of fire evacuation and give a scope to optimize the emergency management plan.

3 METHODOLOGY

An RMG factory is selected for the research purpose. Then, based on the data provided by the factory management, the existing fire risks were analyzed using risk analysis tools.

As a part of data collection, a survey was conducted to have the occupant’s perception about current emergency protocol in the factory.

After analyzing the fire risks and considering previous data regarding the RMG sector, risk ranking criteria is prepared to make fire scenarios in accordance with ISO 16733. Later, an event tree analysis is performed to analyze the uncertainties followed by a risk profile which presents the probability of acceptance of risks and consequences.

To mimic the actual evacuation process at the factory building, Pathfinder, simulation tool, is incorporated based on management data and the survey that was conducted by face to face interview.

4 FIRE RISK ANALYSIS

According to the Fire Service and Civil Defense, Bangladesh (FSCD), 70% of the fire incidents occurred due to electrical short circuit, 10% for smoking cigarettes, 8% for machinery spark, 7% for overheating and 5% for welding spark. Machinery spark arises due to the friction and lack of proper maintenance (FSCD, 2019).

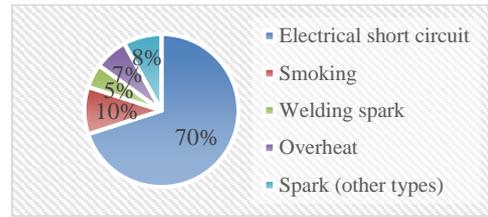


Figure 1: Hazards causing fire incidents in Bangladesh (FSCD, 2019).

4.1 Hazard Identification

As a part of risk assessment, hazards that can cause fire at the factory have been identified and listed as follows:

Table 1: Hazard identification.

SL	Hazards	Description	Mitigation measures
1	Electrical cables or wiring	Electrical short circuit may happen due to poor quality cables and wiring or extra load on cables.	Good quality of electrical materials should be used, and regular maintenance is required.
2	Smoking	Smoldering cigarettes can ignite fire in the smoking area or at the building.	‘No Smoking’ sign should be visible at the building.
3	Frictional mechanical parts	Extra heat (overheat) due to frictions of machines can ignite fire	Proper maintenance of the machines is essential for smooth production.
4	Tube light spark	Spark may arise from the fluorescent tube light used everywhere in the building e.g. warehouse.	Tube light should be checked in regular basis.
5	Chemical ignition	Different types of chemicals are being used in the dyeing section and they can ignite fire.	Chemical should be used with proper care and MSDS should be used strictly for chemicals.
6	Yarns, fabrics	Yarns, fabrics are the flammable materials and they can be a good source for ignition.	Floors should be neat and clean and extra care should be given to the sparks and any other ignition.

4.2 Risk Matrix

Risk matrix, a useful subjective and semi quantitative approach to analyze the risks (Aven, 2008), is applied on the hazard identification for possible fire incidents at the factory building (Table 1).

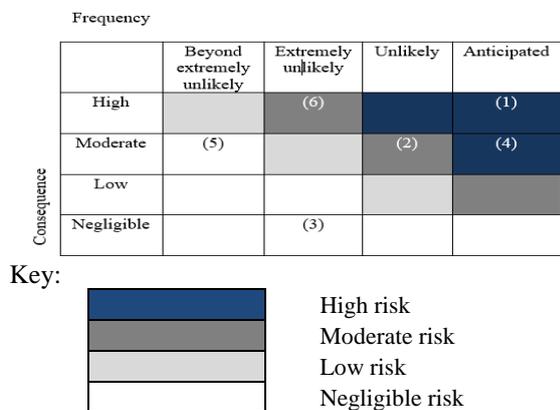


Figure 2: Risk ranking matrix for the causes of fire (based on ISO 16733-1).

In the matrix (Figure 2), the hazards namely electrical cables and tube light spark are placed in the high-risk zone which is marked by blue color. These hazards are serious threats to the fire safety of the building and need immediate attention for mitigation to avoid serious consequences. Smoking and fabrics or yarns are placed in the moderate risk zone and they should be minimized in a short period of time and top management should be informed about these hazards. And finally, chemicals and machines friction can be mitigated through regular checkup.

5 EXISTING EMERGENCY MANAGEMENT

Emergency management has four cycle namely prevention and mitigation, preparedness, response, and recovery (George D. Haddow; Jane A. Bullock; Damon P. Coppola, 2006). This section briefly describes these four cycles in the context of fire related laws and rules.

Table 2: Emergency management at the factory.

Phase	Existing measures
Prevention and Mitigation	Smoke detectors, sprinkler system etc. have been installed as per BNBC. If there are 500 occupants, there should be at least two staircases in the building as per the BNBC. In our factory, they have 4 staircases.
Preparedness	The authority has prepared themselves with in house fire team in each floor who will try to put out fire immediately, rescue team who will be assisting mainly disabled or pregnant women or who get stuck in evacuation, first aiders who will provide first aid to the injured ones, fire extinguishers, hose pipe, hose reel etc.
Response	In-house firefighter will be the first responder and the fire brigade or FSCD will be the second responder.
Recovery	Mainly the fire brigade, in-house fire fighters, in-house rescue team will be in the recovery stage if there is any fire incident. Workers and local people also help in response stage. Local hospitals play vital role in case of casualties in emergency.

6 DESIGN FIRE SCENARIOS

6.1 Fire Safety Objectives

The main objective for the fire safety is to provide life safety to all occupants in the building. The fire safety management should be such a way that no occupant will be exposed to the fire. Occupants must be able to evacuate the building before fire reach critical condition. Hence, the fire safety objectives are as follow:

- Life safety of occupants in the building
- Reduce the property damage
- Reduce environmental impact
- Continuity of factory operations

6.2 Selection Process of Fire Scenarios

ISO has guidelines regarding the selection process of fire scenarios for the evacuation simulation. Based on ISO 16733-1, the following guidelines have been discussed to select fire scenario (ISO, 2015).

Table 3: Selection process of fire scenarios.

Location of fire	In case of readymade garments factory of Bangladesh, ware house is the most potential fire location (Khandoker, M.A.R., Mou, R.J., Muntaha, M.A. and Rahman, M.A., 2018)
Type of fire	Fire involving solid materials like fabrics, clothes, hard board etc. as well as chemicals.
Potential fire hazards	As discussed in Table 1.
Systems affecting fire	Automatic fire detection and alarm system, manual alarm, automatic suppression system (sprinkler), and in-house firefighters.
Occupant's response	Familiar, wake and used to go with the fire drills. But, there may be new occupants, visitors who are not familiar with the building as well as fire safety evacuation.

Event Tree

Deterministic approach has been made to analyze the uncertainties affecting any fire event. The event tree analyzes all the potential outcomes based on the initiating event- starting of a fire at the building. In the event tree, all the existing barriers in the building have been utilized to control the fire incident.

The event tree (Figure 3) has been made based on the data provided by the factory management, but it was not possible to check the correctness of the information used. If any fire incident takes place, there is automatic detection and alarm system installed at the factory and the probability of working this system is 85%. If the automatic system fails, there is 80% probability that this manual alarm works. Sprinklers are being installed and there is 70% probability that they work in case of fire. There are in-house fire team working in every floor. They can suppress fire initially and probability is 60%. The factory management observed during the fire drill that 80% of occupants behave correctly during fire.

In the following event tree (Figure 3), the consequences have been made based on the assumptions and subjective judgment. The number of consequences is the number of occupants who may be exposed to the critical condition and does not necessarily mean casualties or fatalities. For example, in case of fire, if every barrier works and occupants behave correctly, then there will be no one to be exposed to the fire. Sometimes people get panicked just hearing the alarm sound. That is why, there are some consequences in case of fire suppressed in the event tree.

In the following event tree (Figure 3), all the possible fire scenarios and impacts have been calculated.

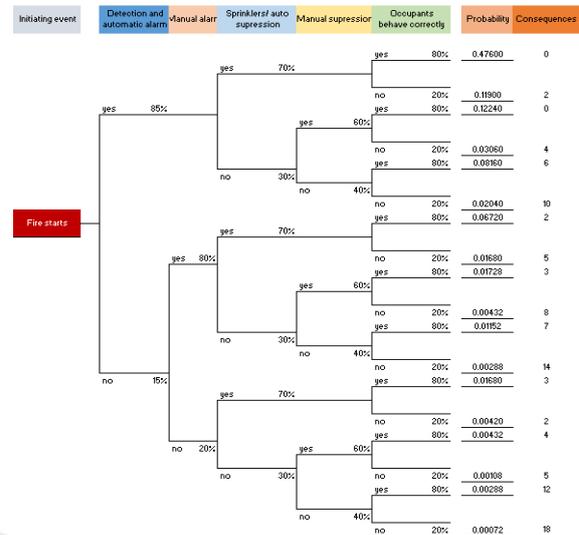


Figure 3: Event tree of fire at the factory building.

6.3 Risk Profile

Risk is defined as the multiplication of the likelihood of an event and the severity of consequences (Aven, 2008). Risk profile has been made from the event tree after calculating the probability and consequence of each scenario. The consequences have been sorted in increasing order with corresponding probability and then cumulative probability has been calculated. Using these impact and cumulative value, the risk profile or staircase function has been drawn and it ranges from probability 1 to 0.

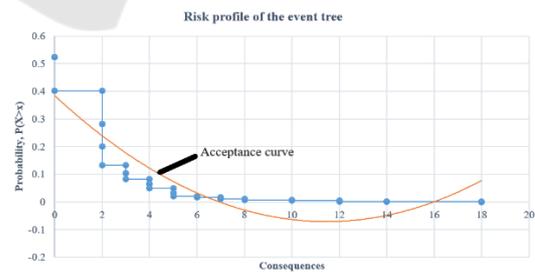


Figure 4: Risk profile curve of the event tree.

Here, the risk profile (Figure 4) shows that the individual risk is 0.52 that means if there is a fire at the building, the estimated probability that one or more occupants are exposed to critical condition, is 0.52. In other words, there is 52 percent chance that

one or more occupants will be exposed to critical condition if there is a fire at the building.

To calculate the medium risk, probability and consequences of each scenario in the event tree has been multiplied and then summed. The medium risk is 1.15 that means, if there is a fire, there will be an average of 1.15 person exposed to critical conditions.

The acceptance curve shows that the management should pay heed to controlling the high probability with zero consequences and high consequences with lower probability zones.

6.4 Fire Scenarios

Fire can be ignited from the electrical short circuit or fluorescent tube light sparks in the warehouse where all the finished goods, yarns etc. are being stored. According to statistics, most of the fire incidents in the apparel industry of Bangladesh starts from the warehouses. As it was mentioned above that, 70% of the fire incidents caused from electrical short circuit (See Figure 1), that is why likelihood of this fire scenario has been set to high. In this case, the fire is ignited in the warehouse during the daytime. In daylight hours, 883 occupants are in the building. The warehouse is in the fifth floor with 2359.55 square meter area and four exits leading to stairs. If fire ignites from any corner of this room, adjacent rooms in the same floor will be affected immediately. The fire and smoke will be spread out to the sixth and seventh floor shortly as the smoke is upper bound in nature. There could be a lot of fire scenarios, hence only this scenario is further discussed as worst case.

7 SIMULATION MODELING

After the analysis of fire risks at the factory and the required information from the survey, evacuation model has been built. The simulation model is built based on the actual drawing and floor layout of the factory building provided by the management. Then the blueprint is produced in .dwg file and further exported to .pth file for extracting floors and doors, stairs etc. in Pathfinder.

In simulation model, factory building characteristics, occupant’s factors and designing of fire scenario have been considered. The building is eight-storied having span of 37161.94 square feet or 3452.46 square meters occupying 883 occupants in total. It has different floors having different layouts comprise knitting, linking, labeling section along with large warehouses. There are egress components such as stairs, lifts by which occupants evacuate

themselves effectively as well as proper ventilation system which takes out the heat and smoke from the building and acts as one of the passive fire protection systems.

Occupant factors has different components such as the number of occupants, age, gender, height and shoulder width, and behaviors of the occupant during fire evacuation. Figure 5 and Figure 6 depict the occupants’ profile, behavior, walking speed, waypoint etc. in the simulation model.

Floor	Occupant's profile	Occupant's behavior	Walking speed
1 st to 4 th floor	Male workers	Go to Any Exit Wait (15.0 s) EXIT Exit <any>	1.19 m/s
	Female workers	Go to Any Exit Wait (15.0 s) EXIT Exit <any>	1.19 m/s
	Pregnant workers	Clients Wait for assist EXIT Exit <any>	1.19 m/s
	Disable workers	Clients Wait for assist EXIT Exit <any>	1.19 m/s
	Management and visitors	Go to Any Exit Wait (15.0 s) EXIT Exit <any>	1.19 m/s
	Fire-fighting team	Fire fighter team Wait (25.0 s) EXIT Exit <any>	1.25 m/s
	Rescue team	Clients Wait for assist EXIT Exit <any>	1.25 m/s for ground floor and 1.19 m/s for rest of the floors
	First aid team	Go to Any Exit Wait (15.0 s) EXIT Exit <any>	1.19 m/s

Figure 5: Occupants profile, behavior and walking speed (1st to 4th floor).

Floor	Occupants profile	Occupant's behavior	Occupants walking speed										
5 th floor	Male workers	Go to waypoint 5 Goto (19.8, 5) Goto (36.8, 3) EXIT Exit <any>	Initial Values: [0] Timed Values: <table border="1"> <thead> <tr> <th>Time</th> <th>Value</th> </tr> </thead> <tbody> <tr> <td>1</td> <td>10.0 s</td> </tr> <tr> <td>2</td> <td>20.0 s</td> </tr> <tr> <td>3</td> <td>30.0 s</td> </tr> <tr> <td>4</td> <td>40.0 s</td> </tr> </tbody> </table>	Time	Value	1	10.0 s	2	20.0 s	3	30.0 s	4	40.0 s
	Time			Value									
	1			10.0 s									
	2			20.0 s									
	3			30.0 s									
4	40.0 s												
Management													
Fire-fighting team													
Rescue team													
First aid team													
6 th floor	Male workers	Go to way point Goto (19.8, 5) Goto (36.8, 3) EXIT Exit <any>	1.25 m/s for fire team and 1.19 m/s for the rest of the floor.										
	Female workers												
	Management												
	Fire-fighting team												
	Rescue team												
7 th floor	Male workers	Go to waypoint Goto (19.8, 5) Goto (36.8, 3) EXIT Exit <any>	1.25 m/s for fire team and 1.19 m/s for the rest of the floor.										
	Female workers												
	Management												
	Fire-fighting team												
	Rescue team												
First aid team													

Figure 6: Occupants profile, behavior and walking speed (5th to 7th floor).

8 RESULTS AND VALIDATION

8.1 Simulation Results and Analysis.

Table 4 shows that the maximum time in steering mode is around 343.40 seconds while 405.20 seconds in the SFPE mode.

Table 4: Results from the simulation model.

	Steering	SFPE
Min	34.7	34.2
Max	343.4	405.2
Average	169.7	176.2
StdDev	76.5	91.3

The figure 7 shows that the time of exit for all occupants is 343.40 seconds. The time is taken by first occupant to exit is around 34.70 seconds is shown in horizontal part of the graph just before sliding down. The steady state of the first occupant from the initial point is due to pre-movement time. After that it slides down at a constant state which means occupants evacuate themselves without any obstacles thus does not create any density in the end.

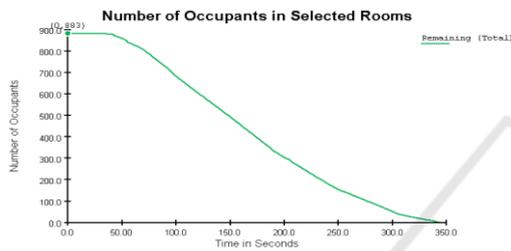


Figure 7: Time of exit for all occupants at the building.

Figure 8 illustrates that, fire breaks out in the warehouse in 5th floor. The two red circles indicate that two exits on the right side of the warehouse are considered to be blocked due to smoke, gas and heat. Thus, all the occupants seek another waypoint which are marked red straight line and seek to safe exits marked yellow circle. Occupant's speed in this floor those who work closest to fire initiating point is affected. Fire fighters stay there to extinguish fire as first responders if needed having the sprinkler system works at the same time.

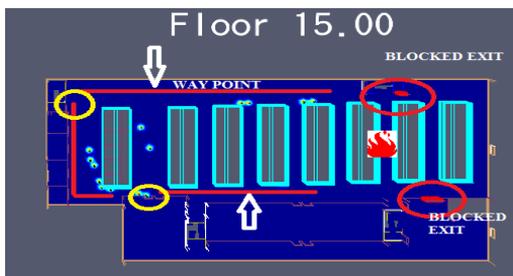


Figure 8: OCCupant's Waypoint Due to Fire in 5th Floor.

Occupants of the two floors which are just above 5th floor do not choose two exits which are blocked in 5th floor due to fire and smoke because of the panic. The panic due to fire lead occupants to choose

the same way points as occupants in the 5th floor seek to leave through safe exit on the other side of the floor.

Waypoints are set up for the safe evacuation purpose (Figure 8). In this kind of situation, occupants might be advised to follow the safe way points for safe exit.

The red marks in Figure 9 indicate that in 2nd floor, there is bottleneck at the exit. This congestion leads to overcrowd at the exit and thus creates panic which might turn out to be stampede instead of safe evacuation.



Figure 9: Density Heat Map in 2nd Floor.

8.2 Validation with Fire Drill Data

Pathfinder simulation tool simulates the evacuation model, verifies the model and validates it with actual fire drill data in terms of total evacuation time (Ahmed, S., Mehmood, S. and Kristensen, A.S., 2019).

The evacuation time from the fire drill is 295 seconds (data was taken from the management) whereas the total evacuation time in Pathfinder simulation (steering mode) is 326.6 seconds. There is a bit difference between two data, because most of the fire drills in most readymade garment factories are announced beforehand that is why there is no pre-movement time.

8.3 Validation with Fundamental Diagram

The fundamental diagram test represents the speed-density profile of the occupants in the model. This test validates the following function:

$$S \approx f(D) \tag{1}$$

Where, speed is a function of density.

For this validation purpose, the 2nd floor of the factory is chosen to examine how the density affects the occupant's speed which reflects the real evacuation scenario. Figure 10&11 represent speed-

density and specific flow-density, and data are represented over time intervals until the steady state arrives.

The simulation is run on steering mode. In steering mode, there is no boundary layers in doors thus does not have any specific flow rate. Here in steering mode, each occupant uses steering system and keep a reasonable distance from others to avoid any kind of obstruction. Each occupant has own specific goal and acts as independent agent. Occupants interact with other occupants.

Figure 10 demonstrates that there is a negative relationship between speed and density so that speed of the occupants is reduced when there is high density.

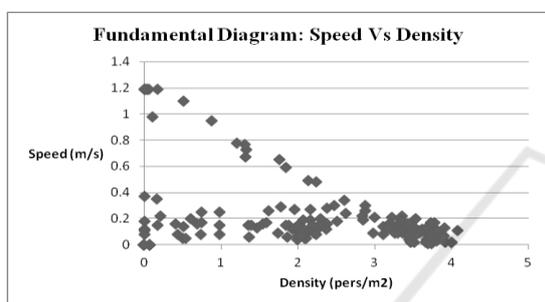


Figure 10: Speed-Density profile.

Figure 11 shows that maximum specific flow is obtained where there is density of 2 person/m². It gets lower when the density is high.

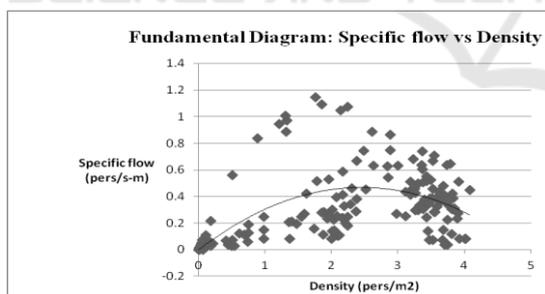


Figure 11: Specific Flow-Density profile.

8.4 Verification with Hand Calculation

The following hand calculation is based on equations in accordance with Engineering Guide to Human Behavior in Fire (Galea, 2003) and considering geometry of the factory building:

If T_1 = the time it takes first occupant to reach controlling component, T_2 = the time it takes to 883 occupants to exit through the controlling components and T_3 = the time it takes the last occupants move from the controlling to component to exit. Then,

$$T(\text{Total evacuation time}) = T_1 + T_2 + T_3 \quad (2)$$

$$T_1 \ \& \ T_3 = d/v \quad (3)$$

$$T_2 = P/F_s (w - BL) \quad (4)$$

$$v = K_t (1 - \alpha D) \quad (5)$$

Where d , v , p , F_s , w and BL means density (1.88 pers/m²), velocity, number of occupants (883), maximum specific flow (1.32 person/s-m), actual width of door (32 inch), boundary layer (6 inch) respectively, and k_t (1.40, 1.08 for corridors and stairs respectively) and α (0.266) are constant.

The total evacuation time by hand calculation is 423.22 seconds. The evacuation time from simulation is 405.20 seconds without pre-movement time closest to 423.22 seconds. This difference is acceptable according to simulation developers (Thunderhead engineering, 2018).

9 DISCUSSION

This study shows that fire can be broken out due to hazards exist in the factory. Despite having fire drills in the factory, it lacks the real evacuation scenario since fire drill is pre-determined in most of the cases and it does not mimic the existence of fire.

The simulation result shows that there could be lot more improvement in terms of further optimization of the emergency management system. For instance, in case of fire, occupants in the warehouse could be advised to choose other exits for safe evacuation. Simulation result clearly shows the option for safe evacuation when other exits are blocked due to fire and smoke.

The result also shows that there could be clogging in any of the exits. In this case, occupants could be advised to go to other exits when they see that the exits they try to get through are highly dense and thus prevent stampede due to panic.

10 CONCLUSION AND RECOMMENDATIONS

Evacuation for a hundred percent export-oriented factory is a difficult task to carry out in emergency. Fire in the factory possesses high risk and has an impact on human lives and properties. As an integral part of the emergency management approach, the fire

drill carried out at the factory which does not reflect the true evacuation process. In the drill, fire and smoke are not created and most importantly, exits are not blocked during the fire drill at the factory. But exits near the fire will be blocked and halt the occupants from safe egress. In Pathfinder simulation, in case of fire in warehouse, exits were blocked near fire location and occupants were assigned to use specific exit route through waypoint to safe exit. Pathfinder provides some extent of behavior based on parametric input from the data from survey. The simulation gives the Required Safe Egress Time and identifies hazardous area in terms of congestion in exits of the floors due to high density which helps assessing the risk. One important drawback is that, Pathfinder cannot predict the real behavior of occupants in case of emergency. Behavior of occupants varies largely based on the experience, training, safety culture etc. However, the Pathfinder simulation largely opens the scope of optimizing the current emergency management approach in terms of adopting different strategy in emergency preparedness, response, mitigation and recovery. To optimize the emergency strategy, following measures can be taken:

Relocating the warehouse to some other places would be the optimal choice for the management of the factory to avoid huge economic loss and loss of lives.

The findings from simulation like clogging, behavior etc. should be taken into consideration during fire drill in mitigation and prevention phase of emergency management.

Quantitative risk analysis tools may be used to assess the fire risks.

The number of occupants in 2nd and 3rd floor should be reduced.

Authority should engage the local people, hospitals and law enforcement agencies in the response and recovery stage.

There should be an incident command system at the factory for handling any emergency at any time (day or night).

This research using risk analysis tools and Pathfinder simulation software can help the entire Readymade garment industries along with other industries and any building structures to assess the risk and to optimize the emergency management in case of fire evacuation.

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