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Planning Construction Rehabilitation Projects Considering Fire Hazards

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Abstract

Based on U.S Fire administration report in 2019, buildings during renovation are at their most vulnerable state and fire is one of the main threats to the safety of constructions. In high-rise buildings there is an increased possibility of associated injuries or fatalities with fire due to the high vertical and horizontal density of occupants. Identifying and investigating safety threats prior to mobilizing construction projects during the construction planning stage can reduce the aforementioned risks. This study aims to develop a framework to investigate the effect of occupant's safety as an additional decision criterion, on the construction schedules. In order to implement this investigation, the schedules of construction planning are used in evaluation modeling. A 3D model in a BIM based environment is employed to model the fire in Pyrosim (FDS Fire simulator). By integration of Pyrosim and Pathfinder (Agent based modelling) two RSETs (required safe exit time) for each scenario is generated as an indicator of safety. This output of the software tools is used in the construction and schedule evaluation. All the construction schedules are evaluated in terms of cost, time and safety. The comparison method by providing indexes for each schedule, nominates one schedule as a result. This framework enables to select the schedules with the minimum risk of fire, while time and cost are considered.

1. Introduction

A report issued by the U.S. Fire Administration in 2019 identified various safety challenges with respect to building construction and renovation. During building renovation, due to accumulation of waste combustibles, limited access, and hazardous operations such as hot work and welding, buildings are at their most precarious state[1]. A tragic example is the 850-year old Notre Dame Cathedral in Paris, which was partially destroyed by a fire during the renovation and restauration process. Notre Dame is just one of many examples of the great loss that occurs caused by fire in building construction and renovation [2]. Safety is an essential factor in construction planning and should be considered as much as other elements such as cost and financial planning, time and scheduling, and equipment management [3]. Fire is one of the main threats to the safety of construction. The *National Fire Protection Association (NFPA)* reported that there were 3840 occurrences of fire in buildings under renovation compared with 2580 occurrences of fire in buildings under construction. Furthermore, a higher rate of fatality was identified in buildings under renovation compared with those under construction; eight civilian deaths versus four civilian deaths, and 49 civilian injuries versus 52 civilian injuries [4]. In high-rise buildings there is an increased possibility of associated injuries or fatalities with fire due to the high vertical and horizontal density of occupants and possible obstructions related to building renovations [5]. During the risk assessment stage, identifying and investigating safety threats and implementing safe planning could potentially reduce the aforementioned risks up to 90 percent [6]. This proves the importance of risk assessment prior to mobilizing construction projects. The questions are how can the threat and risk of fire in the planning stage be identified and how can multi-objective evaluation of cost, time, and risk of the construction project be considered simultaneously.

To address the proposed argument, various investigations on human evacuation in fire emergencies are required. In the real world, there is no possibility for collecting the associated data with evacuation time or human behavior in the process of evacuation due to the emergency with the occurrence of fire. The only available approach is utilization of available technologies in the market like software tools for modelling and simulating of facility, occupants, and fire [7].

By integration of Building Information Modelling (BIM) as a product which is a powerful digital representation and storage of building characteristics in a three dimensional (3D) environment in AEC industry that can be used from conceptual design and planning to execution and even utilization phase, and Pyrosim which is a 3D graphical user interface for the Fire Dynamics Simulator (FDS) various fire intensities could be applied on the building model [8], [9]. This integration happens with the aid of Industry Foundation Classes (IFC) which is a schema for translating the language of different software tools to one another[9]. By importing the output of this integration into Pathfinder, an emergency egress simulator supporting agent-based modelling (ABM), a complete fire and evacuation model can be implemented [10].

This research tries to provide us with an understanding of the associated risks related to various construction scenarios choosing the safest option among possible alternatives with the help of the proposed model.

This work has been in parallel coordination with another ongoing study by Moniri Tokmehdash, and the two reports cross-reference one another.

2. Literature Review

2.1. Evacuation

Previous studies and efforts regarding the evaluation of the safety of evacuation in buildings guide this research to cover more criteria and implement a more realistic model and evaluation. In evacuation modelling existing agent-based simulators are playing an important role to simulate and evaluate the evacuation scenarios [11]. **Agent-based modelling** (ABM) is a system including entities as agents. Each agent is making a decision based on their own situation and a set of rules and formulas [12]. The agents in the ABM model are behaving based on the interactions between agents, and agents with the environment [11]. Pathfinder [10], Anylogic [13], STEPS [14], and Evac [15] are examples of these software tools. Although in a few studies the simulation is done by some calculations without the utilization of these software tools, in most of the research one software tool is used. The evacuation in Cao et al. [7]'s study is based on the SEBES model with smoke effect and blind evacuation strategy [7] without simulating the model in any software tool and relying on formulas and calculations. In this study, the focus of the model is on the characteristics and the location of the fire and width of the exit door. As a result, the width of the exit door is inversely proportional to the evacuation time. The limitation of this method is that some factors such as velocity change and the agent's behavior in fire emergency is not considered [7].

Based on WSP's research on three different evacuation software tools (Pathfinder, Evac, STEPS), while coupling the same FDS file including fire with the completely same characteristics, some limitations, and advantages for each of them are found. Evac has poor visualization compared to other software tools although it has a short set up time due to the similarity of its model to the FDS model. Complex geometries are supported in Pathfinder and STEPS with a satisfying visualization. As a limitation in both software tools, FED could be distorted. This research was done in 2017 and the interaction between agents and smoke is not supported and the agents are not slowed down by the smoke [16]. In a new release of Pathfinder in 2020 the agents are affected by the smoke [17], and this limitation is solved.

BIM based environment helps to deal with more complex models and obtaining more accurate results. Sun and Turkan [11], modelled an evacuation by the use of Anylogic an agent-based modelling software tool and a Revit model LOD300. Anylogic has the capability of importing the dimensional information as a DXF file and assess the human evacuation scenario. This study is on a single-story night club without consideration of the vertical load impact. The critical factors affecting the fire and evacuation in this study are human behavior such as speed, physical characteristics of the building, and fire condition. In Sun and Turkan [11],'s study the author did not have access to the as-built drawings of the case study so that the result is not completely accurate. Another limitation of this study is that the computational time of the modelling is very high so, in some parts the higher data resolution is sacrificed. In Wang et al. [18], research is done by the aid of BIM model as well, in this study the distance of each agent to the closest exit door, as escape distance is measured by BIM's dimension function. The result of this research evaluates the possibility of a safe evacuation in the facility, although the human characteristics and other factors impacting an evacuation scenario are not considered and all the results are based on the extracted numbers and parameters from the Taiwan fire code [18].

The models could be exported as extensions of DXF, DWG, IFC, and FBX. All these extensions are importable into pathfinder in order to have the geometry to generate the routes [17].

In general, two different aspects in terms of modelling the evacuation exists. The horizontal evacuation and the vertical evacuation. Considering the effect of upper floors and bottom floor loads on the evacuation of each floor is critical and it is a key to have more realistic results. In Sun and Turkan [11], Cao et al. [7], and Wang et al. [18]'s studies the multi-story building is not modelled and only the single-story is modelled. Although the vertical evacuation is considered in Li et al. [19] and G.N et al.[20]'s research, the fatigue, group movement, and the movement of disabled people in vertical aspect is not investigated comprehensively.

Calculating the evacuation time is based on different **models and modes** such as SEBES model with smoke effect and blind evacuation strategy, SFPE mode, and Steering mode. As mentioned above, the evacuation in Cao et al. [7]'s study is based on the SEBES model with smoke effect and blind evacuation strategy. The difference between this agent modelling and steering agent modelling which is supported in pathfinder is more complexity and involvement of more contributing factors. As an example, in blind agent modelling there are only 8 directions for the agent to choose the next path although in steering mode the direction in based on 360 degrees [7], [10]. In Li et al. [19]'s study, a four-story university library in China is modelled to investigate the safety of the existing facility against fire and evacuation behavior. This modelling is implemented in Pathfinder in both Steering and SFPE mode [19]. The result of this study demonstrates that the accuracy of steering is more than SFPE mode. It is mentioned that the weakness of SFPE mode is in the interaction between agents and mutual penetration in one spot [19].

There are two different contributing factors in order to model each agent in evacuation simulation, **profile and the behavior of agents** [10]. Profile controls the speed, age, size, and height of the agents and behavior dictates the way the agent behaves during the evacuation. Delays, panic, and running into different directions are in this category. Cao et al. [19]'s model has two different profiles, the only factor in profiles is velocity which is different for slow pedestrians and fast pedestrians, and in the behavior of all agents a 20-second delay is entered as the pre-evacuation time, although Wang et al. [18] has no different velocities in profiles for the agents, one constant speed walk and the flow rate are considered in this simulation modelling [18]. Li et al. [19] provided the profile of young male and females and only one default speed as 1.19 m/s without considering the speed of different agents [19]. G.N et al.[20]'s model is simulated in Anylogic, movement is based on a constant velocity. Age, disability, and genders are not considered and the importance of floor layout in the risk level of evacuation is presented [20].

Considering different speeds for different ages and genders increases the accuracy of the result. Based on SFPE human behavior handbook, agents with different age and gender could have different speeds, which is implemented in this study [21].

2.2. Coupling and Risk Assessment

Risk Assessment of the fire in a building is based on the objectives and approach of the study. In some evacuation research such as G.N et al.[20]'s study no fire is modelled and closure of one door is considered as a result of fire in front of it. Based on the reduction of safe exits in the building layout, the risk of fire in evacuation is evaluated at with the aid of Anylogic software tool. In Yayun and Jia [22]'s research the fire is modelled in FDS and the risk is assessed based on the SVM (Support Vector Machine) theory in machine learning, which has the generalization ability to solve high dimensional and nonlinear problems. Quantitative ranges for two passive (Building area, exit quantity, evacuation exit, protected stairway) and active factors (air load density, automatic fire alarm system, evacuation indicatory sign) impacting the risk of fire are considered. The risk element condition is the flue gas height. If the gas reaches 1.8 m which is the average height of human, it is assumed that the condition is critical, and the time is considered as ASET. The state of risk in this model is classified in 4 grades, safe, relatively safe, relatively dangerous and, dangerous [22].

RSET as required safe escape time and ASET as available safe escape time, are two measurements to evaluate the safety of the design. RSET is usually the travel time of an agent based on the physical movement in available routes. The ASET is usually determined based on the exposure of the agent to the fire products and the state which incapacitation is predicted for the agent. RSET could be calculated in evacuation software tools and ASET is an output of the fire dynamic simulator (FDS) and the evacuation scenario [23]. This is an efficient method in assessing the risk of fire in evacuation of the building.

Sun and Turkan [11] defines different stages of smoke layer based on reaching smoke to a specific height (1.2 – 1.5 m) to calculate the ASET. The output of evacuation analysis and the building properties such as number of exits, width of the door and occupant capacity were taken into a linear regression model to compare the required time of evacuation from the building and the available time of evacuation in different conditions. The result of linear regression model, helps to have better strategies in order to have safer design and the 3D BIM model and FDS provide the hazardous zones and the escape routes.

The ASET and RSET are two outputs from FDS fire modeling and evacuation modelling. By considering the ability of co-simulation in pathfinder and running the evacuation simulation while the impact of smoke is embedded, two different RSETs will be calculated in this study.

2.3. Construction schedule evaluation:

In construction projects, the proficiency and effectiveness of construction schedules should be evaluated by the contractor and the owner [24]. Different efforts has been done to categorize the criteria of assessment of the schedules. GAO developed a guideline with 9 divisions, although these divisions do not provide the details assessment process comprehensively and are focused more on the conceptual elements. In addition, The Defense Contract Management Agency of U.S Government (DCMA) set 14 points schedule assessment as a quality guideline such as lag, lead, float, etc [24]. Different contributing factors are considered in previous studies to evaluate and assess the quality of the schedules. These factors are dependent to the scope of the assessment. For instance, Khalifa and U. Daim [25] in their study by proposing a Multicriteria Decision Making (MCDM) , considered cost, schedule, risk, performance and resources by ranking and weighting each of them in different categories [25].

By investigating the previous efforts, there is a lack in considering safety as an important element for schedule assessment along with other mentioned factors. However, Dilipkumar and Jha [26] introduced a cost schedule safety index (CSSI) and merged all the cost schedule, cost performance, and construction safety factors in one equation to make decision. This index is developed by identifying the potential safety threads from previous literatures and driven data from conducted questionnaire in Indian construction industry. [26] This study is inspired by Dilipkumar and Jha's[26] research.

The aim of this paper is to simplify the evaluation of the contributing factors of the schedules and integrate them with the fire safety simulation result, to compare different possible schedules in construction planning stage.

3. Methodology

This paper is outlining a construction planning considering the safety of fire incidents in Highrise buildings. Implementing this methodology, requires accomplishing five stages separately. 1.Building examination. 2.Constructions scope and planning 3.Fire Modeling (Pyrosim) 4.Evacuation Modeling (Pathfinder) 5.Construction evaluation. These steps are illustrated in Fig. 1.

Figure 1. Steps of the methodology

In building examination, the layout of the building in CAD format in a BIM based environment is examined. In this examination, the type and functionality of the spaces, the area of each space, the connections as corridors, and the safe exit doors, are extracted.

The next step as construction scope is selecting the location of the renovation and the renovation type, as a result the renovation activities are determined and based on the renovation activity the crew types and associated properties are extracted from RSMeans. The number of occupants in the building should be determined by the assumptions based on the building codes, required area per person or by the actual number of existing occupants in the building.

In the stage of construction planning, the number of activities operating simultaneously, provides the list of permutational combinations of all the activities. After obtaining all the combinations, the construction logic such as flow and elimination of non-value-added activities are applied to eliminate some combinations. The operational logic such as reallocation capacity is applied on the remaining combinations. The total duration of each activity is calculated based on the total required job and the daily output of the crew. The remaining combinations and the total duration of each activity, proposes all the possible schedules.

The work breakdown of activities, the order of operating activities, duration of activities and the total duration of the schedule (critical path) is clarified in each schedule. Each schedule is divided into workspace snapshots. The workspace snapshots resemble a static snapshot of the operation that happens during the construction at any point of the time. The next phase as redundancy is eliminating the repetitive snapshots and less critical ones. After finalizing the snapshots, reallocation plans based on the extra available capacity are determined. These plans which elaborates the destination of occupants from locations under construction renovation will be used in the evacuation modelling.

As prior investigations have implemented the method of evacuation modeling by the help of software tools, in this study, Pathfinder an evacuation simulation software tool is chosen to model the evacuation scenarios. Fire scenarios are modelled in Pyrosim software tool, the methodology of fire modelling is explained in Moniri Tokmehdash [27]'s report. Two different pyrosim files are imported into Pathfinder, one the base model without fire, and the other models with fire (fire scenarios). To create a model, final construction snapshots and occupants' properties and reallocation plans are used as the basic information of the modelling. In order to model the evacuation in Pathfinder software tool, first step is floor extraction and door detection, second step is creating the occupants based on 2 criteria, the fixed characteristics as profile such as speed, gender, height and behavioral actions such as waiting and moving toward the exit doors.

In order to couple the Pyrosim (FDS fire result) and Pathfinder the automatic method is used. The only impact of fire in this co-simulation on evacuation is slowing down the agents by applying a speed factor on the speed of agents due to the deduction of visibility range.

In the last part of the investigation, the construction schedules are evaluated based on the cost, time and the safety of each schedule. The element of time is a metric to eliminate schedules with shorter or longer periods compare to the required period in the project. The evaluation of the cost in this study is based on the cashflow and daily cost of each schedule. In the evaluation of the safety, first and foremost the possibility of fatality and casualties are investigated. The schedules having the possibility of fatalities are considered as completely risky and they are eliminated in further evaluations. A number as difference required time of evacuation (RSET) between with fire and without fire cases, is assigned to the other schedules. This time is a representative of the risk of each schedule. The numbers of time cost and safety are multiplied, and the minimum obtained number is a criterion to nominate the schedules. All the schedules are ranked based on the assigned number.

4. Case Study

4.1.1. Building Properties

In this study the 17-storey Engineering, Computer Science, and Visual Arts complex (EV Building) of Concordia University is chosen [28]. This high-rise educational building is located in Montreal, Canada. As it is clearly mentioned in Moniri Tokmehdash's report, this building includes offices, labs, conference and meeting rooms with more than 1000 occupants per day [27]. The 9th floor 3D model is provided for this study although it is not as built. The other floor layouts are assumed the same as this floor in this model. The 9th floor layout is separated into 2 parts, Visual Art part in the north including 6 laboratories and Engineering part in the south of the tower. 35 student offices and 9 staff offices are located in the 9th floor [27].

4.1.2. Renovation Type and Location Selection

According to the distribution of occupants among labs and offices, labs have more occupants compared to the offices. Moreover, the EV Building is considered under operation during renovation making the labs more critical locations during the renovation process. Renovation of the 6 labs in V part of EV building is considered in this study. Another location which is assumed for renovation activities is the corridor. Corridors are the main component of accessing different spaces and having construction site in a corridor may cause partial or complete closure of the entire floor. Therefore, these closures can directly impact the flow of occupants and make disruptions which is very important from the evacuation perspective.

In the process of selecting renovation activity type, two factors are considered. First, hot works as a possible ignition trigger where combustible materials are present. Secondly, renovation requires closure of the entire lab and complete or partial closure of the corridor. Based on these two conditions, ceiling work and duct work both require hot works and complete or partial closure considered for labs and corridors, respectively.

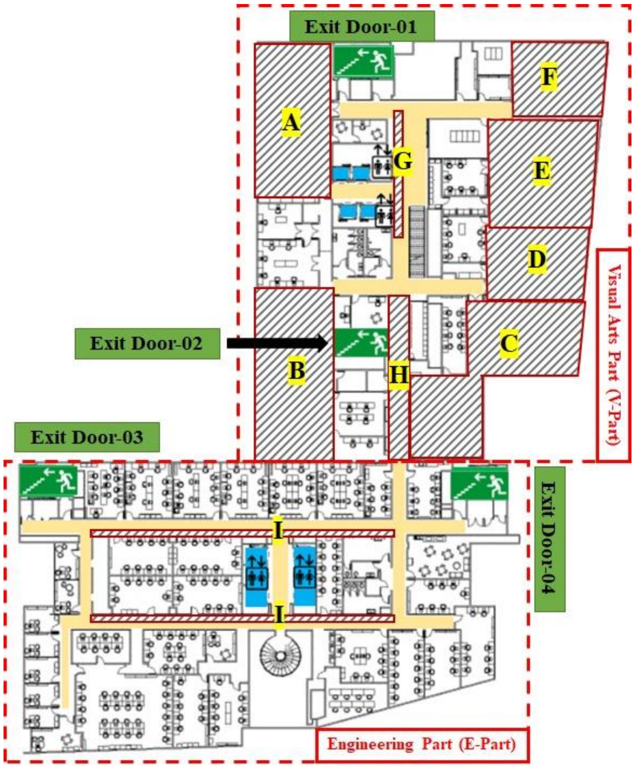

Figure 2. Building layout including construction activities

The ceiling work is assumed for the 6 (A-B-C-D-E-F) labs in the V part of the 8th floor. The duct work is assumed in 3 (G-H-I) corridors in V and E part of the 8th floor of EV building. The G and I operations have partial closures and H renovation has fully closure of the corridor due to the narrower width. All the assumed renovations are illustrated in Fig. 2.

It is assumed that the renovation sites are only accessible for crew members.

4.1.3. Crew Types

After selecting the renovation types, using the 2011 version of RSMeans online data platform, the associated information with both ceiling work and duct work are extracted. Based on RSMeans, for ceiling work, one crew comprised of two workers, with daily output of 500 square foot (S.F) is considered. This means in each workday (8 hours), 500 S.F ceiling work can be done by this crew. For duct work, one crew comprised of three workers with daily output of 265 pounds (lbs) is considered. Daily output of 265 pounds indicates that, based on the material weight of ducts, 265 lbs of the material can be installed each workday. In this study, the productivity of both crew is assumed at 75% of the RSMeans values [29]. Adjusted daily output for ceiling work and duct work are 375 and 198.75, respectively. In addition, cost per day of $60 and $40 are assumed for ceiling work and duct work, respectively.

4.1.4. Calculation of Number of Occupants

4.1.4.1. Occupants of 8th floor

As the access to the university was limited due to COVID-19, the number of occupants in the labs and the offices are assumed based on the Ontario building code. The number of occupants in the offices for the students and faculty are planned for 9.3 sq.m per person, and labs in the V area are planned for 4.6 sq.m per person [30]. Based on these numbers and the extracted area of each lab of the 8th floor from Revit file, the maximum capacity is calculated and the existing capacity as 50 percent of the maximum capacity is assumed, this information is presented in the Table. 1.

Table 1. Labs area and occupant's distribution

				Gender & Age distribution			
Lab	**Area**	**MAX**	**Existing**	**FAMALE<30**	**MALE<30**	**30<FEMALE<50**	**30<MALE<50**
A	187.46	40	20	8	8	2	2
B	192.82	41	20	8	8	2	2
C	187.97	40	20	8	8	2	2
D	106.47	23	11	5	5		1
E	171.36	37	19	7	8	2	2
F	136.23	29	14	5	5	2	2
Total	982.31	210	104	104	104	104	104

The number of occupants in the offices of the 8th floor respects the code of 9.3 sq.m per person and at the same time, it depends on the type of the office. If the office belongs to a professor, one occupant is modelled in that office, although the office has more space. If the office is a shared office the number of occupants follows the capacity based on the code. In Table. 2 all the offices of the 8th floor including the area, maximum capacity and the existing capacity are demonstrated.

Table 2. Offices area and occupant's distribution

				Gender & Age distribution			
Name	**Area**	**Max Capacity**	**Existing**	**FAMALE<30**	**MALE<30**	**30<FEMALE<50**	**30<MALE<50**
E-C-01	29.63	0	0				
E-K-01	41.49	0	0				
E-O-01	35.61	3	1	1			
E-O-02	40.77	4	2	1	1		
E-O-03	40.79	4	2	1	1		
E-O-04	40.66	4	2	1	1		
E-O-05	40.59	4	2	1	1		
E-O-06	40.58	4	2	1	1		
E-O-07	22.52	2	1		1		
E-O-08	37.34	4	2	1	1		
E-O-09	36.93	3	1	1			
E-O-10	40.6	4	2	1	1		
E-O-11	40.52	4	2	1	1		
E-O-12	30.65	3	1		1		
E-O-13	31.63	3	1	1			
E-O-14	39.61	4	2	1	1		
E-O-15	14.17	1	1		1		
E-O-16	41.59	4	2	1	1		
E-O-17	39.48	4	2	1	1		
E-O-18	34.17	3	1	1			
E-O-19	41.67	4	2	1	1		
E-O-20	117.41	12	6	3	3		
E-O-21	39.28	4	2	1	1		
E-O-22	38.79	4	2	1	1		
E-O-23	36.8	3	1		1		
E-S-01	40.56	4	2			1	1
E-S-02	13.28	1	1				1
E-S-03	12.57	1	1			1	
E-S-04	12.9	1	1				1
E-S-05	12.53	1	1			1	
E-S-06	13.66	1	1				1
E-S-07	12.11	1	1			1	
E-S-08	11.07	1	1				1
E-S-09	20.71	2	1			1	
V-C-01	35.6	0	0				
V-O-01	11.85	1	1				1
V-O-02	25.97	2	1	1			
V-O-03	32.59	3	1		1		
V-O-04	23.92	2	1	1			
V-O-05	54.59	5	2	1	1		
V-O-06	9.74	1	1				1
V-O-07	21.6	2	1			1	
V-O-08	31.25	3	1		1		
V-O-09	35.53	3	1	1			
V-O-10	27.28	2	1		1		
V-O-11	19.98	2	1				1
V-O-12	11.68	1	1			1	
Total	**1484.3**	**129**	**65**	**25**	**25**	**7**	**8**

It is assumed that the number of males and females existing in 8^{th} floor are almost equal [31], so that half of the occupants are male and the other half are female. 4 different categories based on age and gender are considered for the occupants.

4.1.4.2. Occupants of the whole building:

The assumption of equal number of males and females is applied on the whole building as well. The categorization of the age and gender in the whole building is the same as 8^{th} floor. The 8^{th}, 9^{th} and 10^{th} floors of the EV building are the fire zones with the same layout, so in this model the number of occupants for these 3 floors are assumed identical. 50 occupants are assumed for the rest of the floors. Table. 3 illustrates the total number of occupants in EV model including the age and gender distribution.

It is also assumed that the construction renovation is occurring only on the 8^{th} floor of the building. The number of crew members operating in each lab and the corridor is two and three, respectively. That is why the total number of occupants in 8^{th} floor depends on the construction renovation type and activity. For instance, if the snapshot includes, I segment of corridor renovation, the number of crew operating in that section is 6, 2 groups of 3 people, although the G part has one group of 3 people. Table. 3 demonstrates the gender and age distribution of the whole building. It is worth mentioning that the crew members have the same characteristics as male<30. These characteristics will be applied in the evacuation modelling.

Table 3. Occupants distribution in the whole building

Occupants' Gender & Age Distribution						
	FAMALE<30	MALE<30	30<FEMALE<50	30<MALE<50	Crew	Total
GF	13	12	13	12	0	50
1	13	12	13	12	0	50
2	13	12	13	12	0	50
3	13	12	13	12	0	50
4	13	12	13	12	0	50
5	13	12	13	12	0	50
6	13	12	13	12	0	50
7	13	12	13	12	0	50
8	66	67	17	19	13	182
9	66	67	17	19	0	169
10	66	67	17	19	0	169
11	13	12	13	12	0	50
12	13	12	13	12	0	50
13	13	12	13	12	0	50
14	13	12	13	12	0	50
15	13	12	13	12	0	50
Total	367	357	220	213	13	1170

In this model total number of occupants in the building is considered 1170 including crew members, and without crew members as 1157.

4.2. Construction

4.2.1. Construction Scenarios

In this section, all the possible construction scenarios are evaluated. Construction scenarios are a result of a workspace planning based on the layout of the floor and the capacity of the labs and offices. To obtain the most efficient construction scenarios, some filtrations are applied. These three steps of filtration are applied which is shown in Fig. 3,these steps will be explained in the following sections.

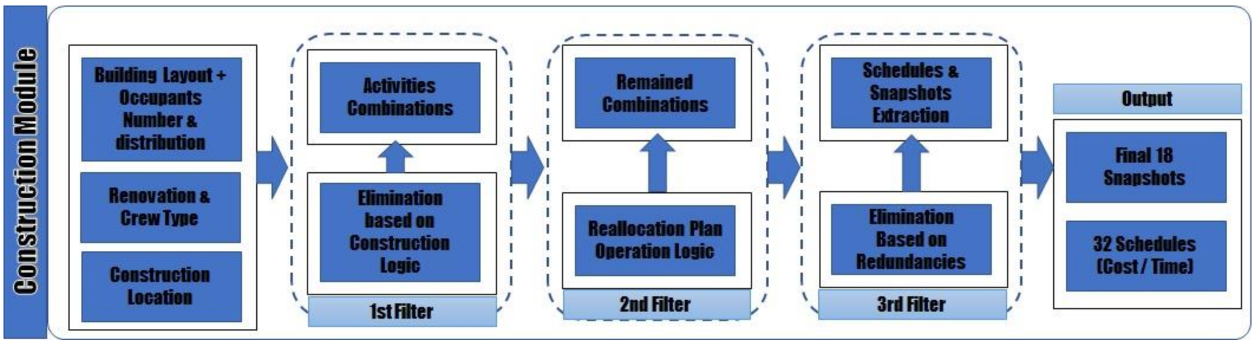

Figure 3. Construction Module

4.2.1.1. Construction Activities Combination:

It is assumed that there are 2 different construction renovation activities which is explained clearly in section 4.1.2. The ceiling work renovation is occurring in the labs and the duct work is in the corridors. 6 Labs and 3 corridors sections are under renovation. In each lab and each corridor section only one crew can operate. The crew types and the properties of RSmeans are mentioned in section 4.1.3. The work is identical in each type of activity. Two, three and four activities could occur simultaneously. These three alternatives are based on the renovation type and the number of crews working at the same time. The three activities are:

- One crew for labs, one crew for corridors/ Two activities (1crew-1crew)
- Two crews for labs and one crew for corridors/ Three activities (2 crews-1 crew)
- Two crews for labs and two crews for corridors/ Four activities (2 crews-2 crews)

Before applying any construction and operation limitation and logic, the total number of permutational combination for 6 labs and 3 corridor sections is 4320.

4.2.1.1.1. Construction flow:

The construction logic should minimize the non-value-added activities. In the first stage due to the avoidance of the occupant's disruptions and having minimum movement time, the movement flow of the construction crew is considered. Lab A, B, C, D, E, and F should be operated one after each other. The logic is applied on the corridor's sections as well. From G to H and I or from I to H and G. The flow of the construction depends on the number of activities occurring simultaneously. In case of 1 crew-1 crew, there is one activity in the labs and one activity in the corridors, based on the layout of the EV building there are 16 possible combinations. For the next alternative which is 2 crews-1 crew and the last alternative 2 crews-2 crews, eight possible combinations exist for each alternative. It is worth mentioning that in cases of having 2 crews for the same activity, the scope of work is identical.

As a result, by applying this construction logic on all the possible combinations, 32 combinations is acceptable, which is illustrated in Table. 4.

Table 4. Combination of activities based on construction logic

Combination of activities based on construction logic				
Location	**Activities**		**Possible combinations**	**Total after elimination**
Labs	**a-b-c-d-e-f**	**1 crew**	**16**	**32**
Corridors	**g-h-i**	**1 crew**		
Labs	**a-b**	**1 crew**	**8**	
Labs	**c-d-e-f**	**1 crew**		
Corridors	**g-h-i**	**1 crew**		
Labs	**a-b**	**1 crew**	**8**	
Labs	**c-d-e-f**	**1 crew**		
Corridors	**g-h**	**1 crew**		
Corridors	**i**	**1 crew**		

4.2.1.1.2. Operation logic:

Evaluating the occupant's reallocation is based on the available minimum area per person. In the stage of building operation filtration, the possibility of occupant's reallocation is considered. This calculation is based on the minimum area per person in the labs and offices, the number of existing occupants in each lab and office, is mentioned in section 3.1.2.

In Table. 5 the area of each lab, existing occupants and the extra load capacity are listed. In this stage some combinations could be eliminated due to the lack of enough space for reallocation. It is also assumed that the occupants should be reallocated into the same functionality of the room. Labs into the labs and offices into the offices. There is no renovation in the offices, although some of the offices due to the lack of accessibility should be reallocated to other offices. The reallocation of the offices is not a challenge in this study. The maximum number of occupants in each snapshot requires reallocation into the offices is three, this space is always available on the 8th floor of EV building. The reallocation of the offices is only efficient in the modelling and not in the filtering and elimination stage.

Table 5. Extra capacity of the labs

Lab	Area	MAX	Existing	Extra capacity
A	187.46	40	20	20
B	192.82	41	20	21
C	187.97	40	20	20
D	106.47	23	11	12
E	171.36	37	19	18
F	136.23	29	14	15
Total	982.31	210	104	106

In Table. 6 the accepted combinations are listed. If the total number of occupants in 2 labs are more than the extra capacity of the other available 4 labs, the combination should be eliminated. In this case, all the combinations are accepted and the space in other 4 labs support the occupants of 2 labs under construction.

Table 6. Available capacity in the combination of activities

Activity 1	Activity 2	Act1+Act3	Total Extra Capacity	Available Capacity
A	B	40	65	25
A	C	40	66	26
A	D	31	74	43
A	E	39	68	29
A	F	34	71	37
B	C	40	65	25
B	D	31	73	42
B	E	39	67	28
B	F	34	71	37
C	D	31	74	43
C	E	39	68	29
C	F	34	71	37
D	E	30	76	46
D	F	25	79	54
E	F	33	73	40

4.2.1.2. Scheduling and Extracting Snapshots

To calculate the duration of each combination extracted in section 4.2.1.1, the job work required for each activity is calculated based on the daily output of the crew operating in the activity mentioned in section 4.1.3.

4.2.1.2.1. Ceiling work:

In the ceiling work, the area of each lab is extracted from Revit model, the area is doubled because the removing and installing activities are embedded in one activity. The total area of each lab is divided to the adjusted daily output of the crew (renovation of the determined crew), to calculate the duration of the renovation executed by that specific crew. In Table. 7 the total ceiling work duration and the breakdown of each lab duration is illustrated.

Table 7.Ceiling work activities

Ceiling Work					
Activity	**Area**	**Area**	**Remove &**	**Duration**	**Duration**
	(m2)	**(Sq.ft)**	**Install**		**(round up)**
A	188	2461	4922	13.13	14
B	193	2676.4	5352.8	14.27	15
C	188	2030.4	4060.8	10.83	11
D	107	1155.6	2311.2	6.16	7
E	172	1857.6	3715.2	9.91	10
F	137	1479.6	2959.2	7.89	8
Total	**985**	**11660.6**	**23321.2**	**62.2**	**65**

4.2.1.2.2. Duct work:

Galvanized steel (Gauge 18) duct is assumed as the material of the ducts. The galvanized steel properties are extracted from engineering toolbox [32]. The properties and the weight per square feet is shown in the Table. 8 the unit of duct work in RSmeans is weight (lb/s.f), that is why the total weight of the ducts in the corridors is calculated to obtain the duration of renovation.

Table 8. Galvanized steel (Gauge 18) properties

Dimensions				Area / 1 ft (S.F)	Thickness	Weight (lb/S.F)
W (inch)	**W (ft)**	**H (inch)**	**H (ft)**			
30	**2.5**	**10**	**0.83**	**6.66**	**1.024**	**2.156**

In the next step, to find the required job and duration, the total weight of the ducts in three sections of the corridors are calculated. The length of the duct is multiplied to the area per foot (6.66) to obtain the total area of each segment of the corridor. The total weight is calculated by the multiplication of the total area and the weight per square foot. By adding the total weight of three segments of the corridor the total weight of duct work is calculated, which is shown in the Table. 9.

Table 9. Duct work activities' weight

Duct Work				
Activity	**Length (m)**	**Length (Ft)**	**Area**	**Weight**
G	23	76	506.16	1091.28
H	23	76	506.16	1091.28
I	38	125	832.50	1794.87
Total	**84**	**277**	**1844.82**	**3977.43**

Same as the ceiling work, to calculate the duration of each activity in the corridor the total job is divided to the adjusted daily output (renovation of the determined crew). Table. 10 shows the total duration for each segment activity of the corridors.

Table 10. Duct work activities

Duct Work			
Activity	**Weight/1 ft**	**Duration**	**Duration (round up)**
G	1091.28	5.49	6
H	1091.28	5.49	6
I	1794.87	9.03	10
Total	**3977.43**	**20.01**	**22**

4.2.1.2.3. Generating schedules:

After calculating the duration of each activity, the 32 combinations are scheduled. As it is mentioned before, three alternatives are assumed for the combinations and crews operating at the same time. By scheduling the work breakdown for labs and corridors, the order of the activity operation, (based on the combination), and the total duration of each schedule will be clarified. In this step the schedule is divided into workspace snapshots. The workspace snapshots resemble a static snapshot of the operation that happens during the construction at any point of the time.

Fig. 4. is a sample of 1crew-1crew schedule:

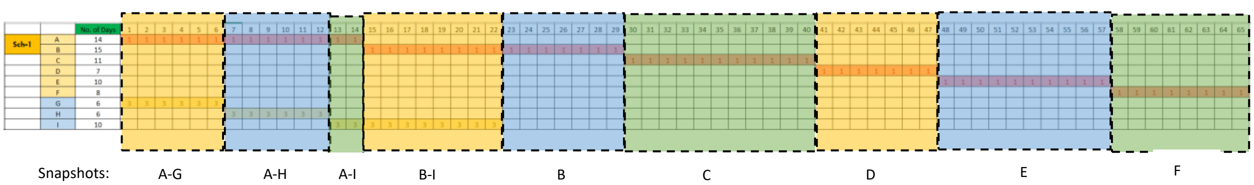

Figure 4. 1 crew - 1 crew schedule sample

This schedule represents the flow of A-B-C-D-E-F for the labs and G-H-I for the corridors. In number of days column, the duration of each activity is specified. Each workspace snapshot with different durations for this specific schedule is presented in Table. 11.

Table 11. Snapshots of schedule 1

From	To	Act1	Act2
1	6	A	G
7	12	A	H
13	14	A	I
15	22	B	I
23	29	B	
30	40	C	
41	47	D	
48	57	E	
58	65	F	

In Fig. 5 a sample of 2 Crew-1 Crew is shown:

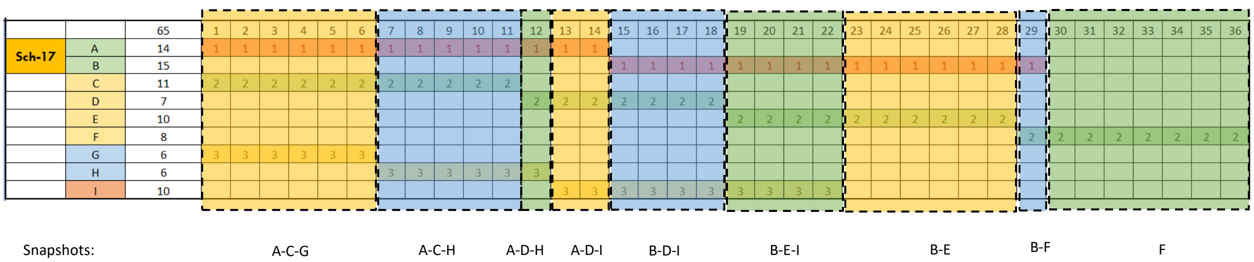

Figure 5. 2 crew- 1 crew Schedule sample

This schedule has one extra activity of lab, having two activities in the labs made the schedule shorter and instead of 65 days the critical path duration is 36 days. While one crew is operating in the lab A another crew with the same type is operating in the lab C. They respect the construction flow logic and crew No.1 moves from lab A to lab B and crew No.2 moves from lab C to D and from D to E and F. Table. 12 Demonstrates the workspace snapshots of this schedule.

Table 12. Snapshots of schedule 17

From	To	Act1	Act2	Act3
1	6	A	C	G
7	11	A	C	H
12		A	D	H
13	14	A	D	I
15	18	B	D	I
19	22	B	E	I
23	28	B	E	
29		B	F	
30	36	F		

The schedule of a presentative of the last alternative (2 Crew- 2 Crew) is shown in Fig. 6.

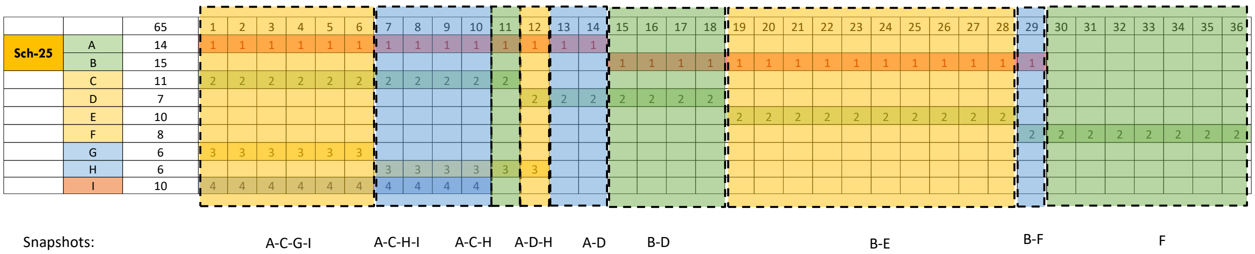

Figure 6. 2 crew - 2 crew schedule sample

Two activities in the labs and two activities in the corridors are operating at the same time. The duration of the schedule I same as (2 crew- 1 crew) alternative, because the critical path duration does not change. The snapshots and corresponding durations are illustrated in Table. 13.

Table 13. Snapshots of schedule 25

From	To	Act1	Act2	Act3	Act4
1	6	A	C	G	I
7	10	A	C	H	I
11		A	C	H	
12		A	D	H	
13	14	A	D		
15	18	B	D		
19	28	B	E		
29		B	F		
30	36	F			

In all the schedules activity number one and two have the same scope and crew type (ceiling work), and the activity number three and four are the same (duct work). Each schedule is consisting of several snapshots. As a result, each schedule has 9 different snapshots with different durations. 288 snapshots are extracted from all 32 schedules.

4.2.1.2.4. Redundancy:

The next phase is eliminating the repetitive snapshots and less critical ones. All the 288 snapshots are compared. All the snapshots of the alternative including 2 activities (1 crew-1 crew), exist in more critical snapshots in other alternatives. Thus, all snapshots coming from 16 schedules of (1 crew-1 crew) are eliminated. For instance, if there is a snapshot including 2 activities of A-D from 1 crew - 1 crew, and there is another snapshot from 2 crews-2 crews including A-D-H-I, the first snapshot should be eliminated due to the less criticality.

The snapshots of the rest 16 schedules are compared, and the result is 18 final snapshots. 2 crews-1 crew alternatives including three activities, has 7 critical snapshots after the redundancy elimination and the last alternative 2 crews-2 crews has 11 final critical snapshots. Table. 14 demonstrates all the final snapshots:

Table 14. Final Snapshots

Final Snapshots			
Activity 1	Activity 2	Activity 3	Activity 4
B	C	G	I
B	F	G	I
A	C	G	I
A	E	G	I
A	F	G	I
B	C	H	I
B	E	H	I
B	F	H	I
A	C	H	I
A	E	H	I
A	F	H	I
B	D	I	
A	D	I	
B	D	H	
A	D	H	
B	D	G	
B	E	G	
A	D	G	

4.3. Reallocation Plan

After finalizing the snapshots, reallocation plans based on the extra capacity of other labs is determined. These plans which elaborates the destination of occupants from labs under construction renovation will be used in the evacuation modelling. In all the reallocation plans even distribution is considered.

In the 18 final snapshots, 2 labs are under construction. The reallocation of 2 labs combinations to other 4 available labs are modeled in 8 different plans. Reallocation plans of (A-C), (A-F), (B,E), (A,D), (B,C), (B,F), (A,E), and (B-D) are illustrated in Fig. 7 to 14 These plans will be used in evacuation modelling.

Labs A-C reallocations:

Figure 7. Labs A-C reallocation

Labs A-F reallocations:

Figure 8. Labs A-F reallocation

Lab B-E reallocations:

Figure 10. Labs B-E reallocation

Lab A-D reallocations:

Figure 9. Labs A-D reallocation

Lab B-C reallocations:

Figure 12. Labs B-C reallocation

Lab B-F reallocations:

Figure 11. Labs B-F reallocation

Lab A-E reallocations:

Figure 14. Labs A-E reallocation

Lab B-D reallocations:

Figure 13. Labs B-D reallocation

4.4. Evacuation Modelling (Pathfinder)

As prior investigations have implemented the method of modeling by the help of software tools,

in this study, Pathfinder an evacuation simulation software tool is chosen to model the evacuation scenarios. Pathfinder calculates the egress time based on two different methods, SFPE method which is introduced by Society of Fire Protection Engineering and Steering mode, which is an artificial intelligence model performing based on each occupant's decision in a dynamic environment [10]. In this research Steering mode is chosen to run the simulations and evaluate the evacuation scenarios.

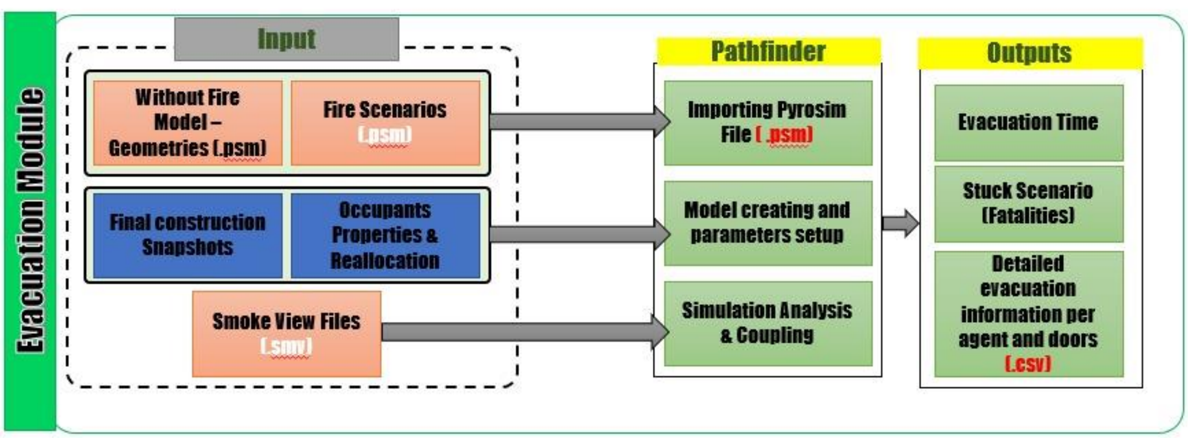

Figure 15. Evacuation Module

The first input of the pathfinder is the model, although pathfinder supports importing the Autodesk formats such as DWG, DXF, and DAE and also buildingSMART's IFC, in this research because of the utilization of Pyrosim in order to model the fire before modelling the evacuation, Revit models are imported into Pyrosim first and the output of pyrosim (.psm) is imported into pathfinder software tool. This extension includes the geometries of the Revit model and is sufficient for the evacuation modelling. Pathfinder materials are constructed from the color and texture settings of the surfaces in Pyrosim, although it has zero impact on the modelling of evacuation.

Two different pyrosim files are imported into Pathfinder, one the base model without fire, and the other models with fire (fire scenarios). To create a model, final construction snapshots and occupants' properties and reallocation plans are used as the basic information of the modeling. All the mentioned steps are shown in Fig. 15.

The evacuation modelling is done on a laptop with following configuration:

- Intel dual-core i5 processor (2.5 GHz)/ 8GB RAM

The simulations are done on a computer with following configuration:

- Intel quad-core Xenon processor E5 v5 family with 32 GB RAM

4.4.1. Pathfinder modelling:

4.4.1.1. Floor extraction and Door detection:

After importing the model into Pathfinder, the first step is floor extraction and door detection. In case of importing IFC or Autodesk formats this step can be automated, in this simulation because of importing the Pyrosim file, this step is manual. In addition, generating the floor extraction automatically has some limitations such as recognition of the exact width and length of the doors [17]. However, all the floors could be copied, and this manual job is performing only for one floor which is identical in this model.

All the furniture such as desk and table are modelled in Revit. By extracting the floor, the software determines the location of the furniture as hole in the floor plain. At the early stage of modelling, the furniture was modelled with curves, these curves made the pathfinder model super heavy due to the triangled meshes of the floor plain and in order to optimize the model all the curved furniture changed to the rectangles shape.

The 8 floor extraction is copied to create the other floors. As it is mentioned in the case study, the As-built models were not accessible so that all the floors are assumed with the same layout.

The pressurized safe exit staircases are modelled to be able to evaluate the vertical evacuation as well as horizontal evacuation. However, two unpressurized stairs, one in V part and the other in E part (the spiral one) is not modelled in the evacuation simulation. Based on the regulation of Concordia University Fire Marshal [28], these stairs are not safe and should not be considered as a safe evacuation stair. Elevators are not modelled, using the elevators in the emergency evacuations is not safe and they are shut down during the evacuation.

The constructions sites are not accessible for occupants to go through them in the evacuation scenario.

4.4.1.2. Creating Occupants:

Occupants are defined based on 2 criteria, fixed characteristics as profile such as speed, and sequence of actions as behavior such as waiting [17].

4.4.1.2.1. Creating Profiles:

In profile of agents, there are characteristics of the agent, movement options, door choice, output and advanced option which are all based on the default of the software tool except the speed. Quantitative parameters could be specified in pathfinder in 2 different methods, Constant value, or a probability-based value (Uniform, Normal, and Lognormal). There are two different types of speed library, fruin and IMO. In this study the IMO speed profiles are imported into pathfinder. As mentioned in section 4.1.4.1, there are 4 different profiles with different speed ranges. Different speeds based on the age and gender is illustrated in Table. 15.

Table 15. Occupants speed distribution

Occupants' Speed Distribution (m/s)				
FAMALE<30	MALE<30	30<FEMALE<50	30<MALE<50	Crew
0.93-1.55	1.11-1.85	0.71-1.19	0.97-1.62	1.11-1.85

In the speed section the advanced option is chosen, the speed value choose is based on Uniform probability; the system generates random speeds for each agent in the specified intervals which are uniformly distributed.

The speed-density profile set the speed of each agent as function of density. It is based on the imported library, which here is IMO. As an example for the profile of females under 30 year-old, the speed density diagram is shown in Fig. 16.

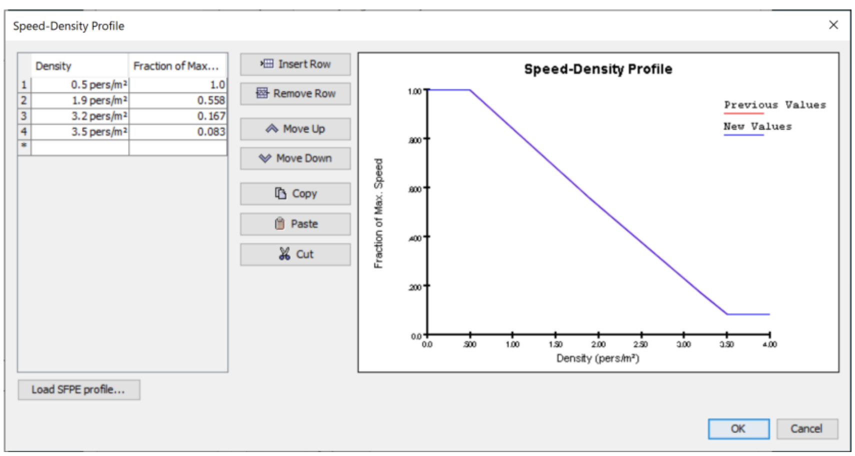

Figure 16. Speed density profile [17]

In the characteristics of the profile, there is no priority for a specific profile, it means all the profiles have the same weight and priority in evacuation. The diameter and the height of all agents are set as 45.58 meter and 1.8288 meter, respectively. The specified height of agents is important in visibility and the impact of smoke on them to be slowed down. It means the agent's visibility is measured at their height level [10].

In the movement section, all the doors, rooms, and stairs are available for all the agents and there is no restriction in choosing a path. Cost factors for room travel time, room queue time and global time are set as one in door choice section. These cost factors affect the cost of travelling to a door, waiting in a queue at a door in occupant's current room, and travelling from a door to an exit. These cost factors can apply changes in one specific profile. In our model all these costs are set as one [17].

In the output section, there is a print CSV data, if it is checked one additional CSV file will be generated including all the information of the agents from this profile. This file includes, speed, and the walked distance in the time step per second. As a result of enabling this feature, more resources such as CPU and disk space will be used. In this study print CSV data is checked only for one case out of ninety scenarios including all the profiles and agents of the 8th floor [17].

4.4.1.2.2. Creating Behavior:

The one and only behavior set for all the profiles is "Goto Any Exit". To follow this behavior all the occupants by using the fastest route move to any exit.

In behavior of agents there is an option which is wait time, this is the time from ignition to detection and alarm before occupants start to evacuate. However, in this study no wait time is considered, and this limitation is compensated by setting a constant HRR is fire modelling as Moniri Tokmehdash [27] mentioned in his report. No extra actions in the behavior, change in behavior or profile and assistance requirement is modelled. Disabled occupants which require assistance are not considered as well.

4.4.2. Coupling / Co-simulation

In order to couple the Pyrosim (FDS fire result) and Pathfinder there are two methods, the first is manual by using the Walking speed in smoke function based on the visibility of occupants. In this method some devices should be modelled in the Pyrosim software tool and these devices measure the visibility in their location. The factor speed could be calculated based on below formula [10].

Equation 1. Speed factor $$factor_{speed} = min(1, max(0.2, 1 - 0.324 * (3 - vis)))$$

Visibility (m)	Factor
0.000	0.200
0.647	0.200
3.000	1.000
5.000	1.000

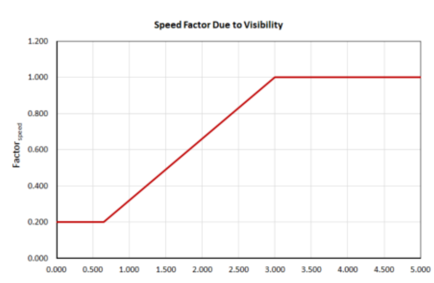

Figure 17. Speed factor due to visibility [17]

The speed factors should be input into the pathfinder manually as a speed modifier. After completing the table for all the time steps (1s) of evacuation, the manual coupling is done, and the simulation analysis could be run.

The second method (automated), is importing the smoke view file, one of the output files of Pyrosim software tool. This file should be imported into the FDS data of simulation parameters.

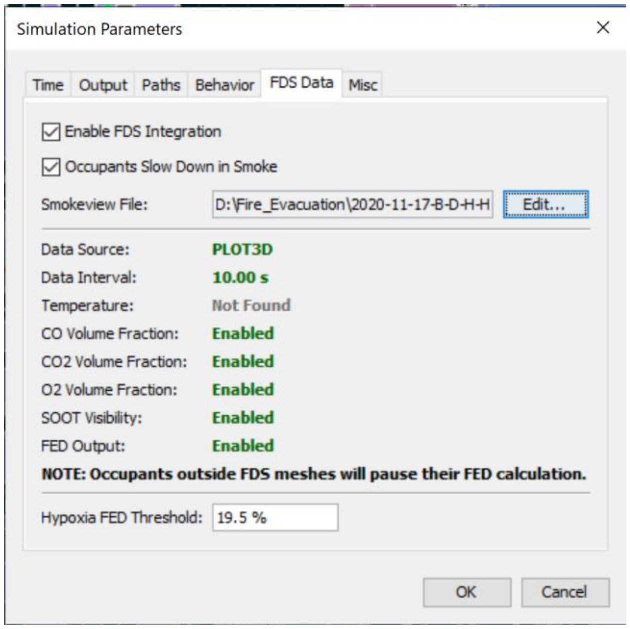

Figure 18. Simulation parameters

The data interval of the coupling is set as 10 seconds in all the 90 scenarios. The FDS integration and the Occupants slowdown in the smoke are checked to make the Pathfinder able to reduce the speed of the agents due to the smoke. Although the CO, CO2, O2, and FED are imported by the PLOT3D, they do not have any impact on the occupants in the evacuation simulation. If the print CSV data is checked, all these volumes and amounts are reported for each agent in an excel file. The only factor affecting the occupants in a fire evacuation simulation in Pathfinder is smoke which decreases the visibility and as a result changes the speed of the occupants [17]. The simulation parameters are illustrated in Fig. 18.

The analysis time of each evacuation simulation by Pathfinder is between 10 to 15 minutes.

5. Results and Discussion

5.1. Results

5.1.1. Construction Planning Results (Time & Cost)

According to the final construction scenarios mentioned in section 4.2.1, at the end of the process 32 schedules are generated which based on the total amount of work, daily output and cost per day of each crew, and possible crew combinations, total project duration and total cost are calculated and presented in the Table. 16. In accordance with this Table, total durations are 65 days for 1 crew – 1 crew and 36 days for 2 crews – 1 crew and 2 crews – 2 crews alternatives. Additionally, all the total costs are the same which is $4,780.

Table 16. Total cost of schedules

Schedule Type	Schedule Number	Crew Combination	Total Duration (Days)	Total Cost ($)
1	Schedule 1 to 16	1 crew (lab) – 1 crew (corridor)	65	4,780
2	Schedule 17 to 24	2 crew (lab) – 1 crew (corridor)	36	4,780
3	Schedule 25 to 32	2 crew (lab) – 2 crew (corridor)	36	4,780

5.1.2. Construction Planning Results (Safety)

The result of co-simulation of Pathfinder and Pyrosim consists of two RSETs (required safe evacuation time). The first RSET is the result of 18 snapshot simulations without fire. These 18 RSETs are considered as baseline of safe evacuation time. The second RSET is the result of 90 snapshot simulation with the impact of fire. All the results are presented in Moniri Tokmehdash [27]'s report.

5.1.3. Construction Schedule Evaluation

In this study three metrics are considered for the schedules evaluation: 1) cost, 2) time, and 3) safety which each of them has a specific evaluation process. Based on the proposed formula in Equation 9, by multiplying the calculated numbers associated with each petameter, one number will be obtained. After calculating this number for all schedules, the one has the smaller value will be the nominated in this evaluation.

5.1.3.1. Cost Evaluation

As it shown in the construction planning results section, all the total costs associated with each schedule is $4,780 due the assumption of identical crews for duct work and ceiling work when there are 2 crews in the same activity. So, in this case, total cost is not a proper metric for cost evaluation. For the purpose of cost evaluation of the construction schedules, cash flow analysis on a daily basis is considered as a metric for this process.

By calculating the cost per day in the cash flow of all 32 schedules, they are divided into 3 types which are illustrated in the Fig. 19, 20 , and 21.

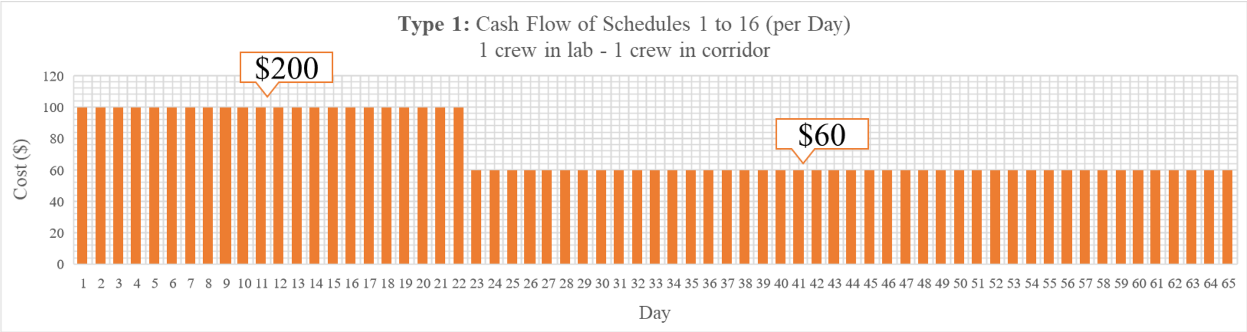

Figure 19. Cashflow schedule type 1

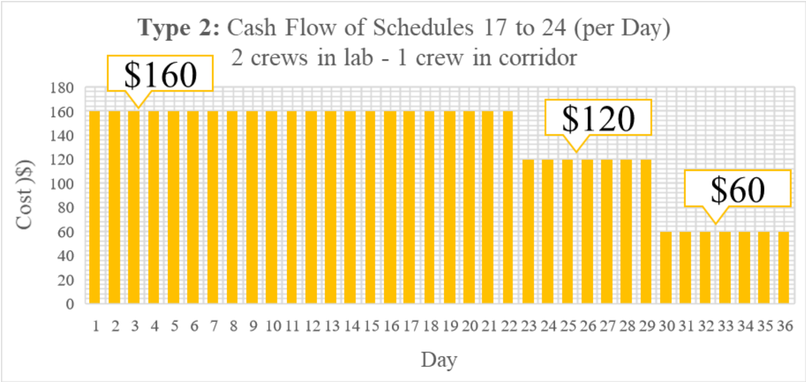

Figure 20. Cashflow schedule type 2

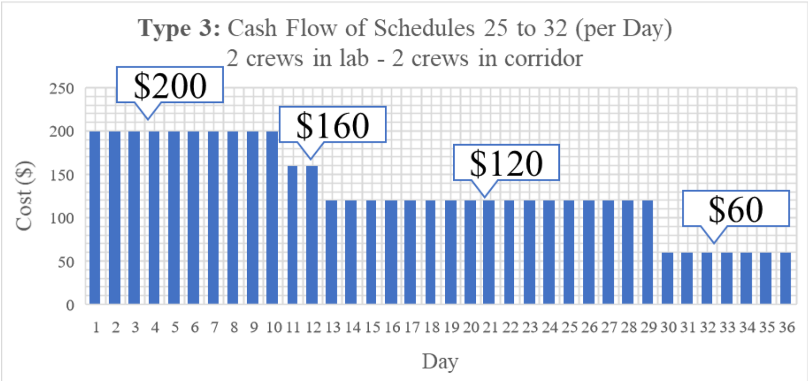

Figure 21. Cashflow schedule type 3

In terms of objective for this evaluation, the less cost is considered. For the accomplishment of proposed objective, mode cost is selected to rank three types of schedules. The mod cost is the cost which has been repeated the longest time. Based on that, the mode cost for each schedule is calculated in the Table. 17 and is sorted from smallest to largest.

Table 17. Schedule mode cost

Schedule Type	Schedule Number	Crew Combination	Mode cost
1	Schedule 1 to 16	1 crew (lab) – 1 crew (corridor)	$60
2	Schedule 17 to 24	2 crew (lab) – 1 crew (corridor)	$120
3	Schedule 25 to 32	2 crew (lab) – 2 crew (corridor)	$160

As shown in Table. 17, schedule type 1 with $60, has the least mod cost among all the 3 types. The second smallest mod cost is associated with schedule type 3 with $120 and the largest mod cost between these 3 is $160 which is for schedule type 2.

5.1.3.2. Time Evaluation

Time or in another word duration of schedules is another contributing factor in the construction planning evaluation. In this study the objective of time evaluation is selected as shorter time of schedules. In addition, it is assumed that this renovation is undergoing in the duration of the exam time in the university and there is a high demand of students for accessing to their labs. Therefore, any schedule with more than 60 days is not acceptable. Based on this assumption and the proposed objective, schedules are sorted from the smallest to largest duration in the Table. 18.

Table 18. Schedule duration

Schedule Type	Schedule Number	Crew Combination	Duration (day)
1	Schedule 1 to 16	1 crew (lab) – 1 crew (corridor)	65
2	Schedule 17 to 24	2 crew (lab) – 1 crew (corridor)	36
3	Schedule 25 to 32	2 crew (lab) – 2 crew (corridor)	36

As listed in Table. 18, schedule type 1 is eliminated because its duration is more than 60 days. The schedule types 2 and 3 with the same duration of 36 days are acceptable for the further evaluation.

5.1.3.3. Fire and Evacuation Safety

Two different methods as A and B are proposed in terms of evaluation of safety and evacuation time.

5.1.3.3.1. Method A:

In safety analysis, the first and foremost is the possibility of casualties and fatalities. In this study 8 out of 90 snapshots have the possibility of fatality by the chance of getting stuck in V part of the

8th floor. If the fire occurs in front of Exit-Door-01 and the H part has construction (closure of Exit-Door-02), the agents in V part will be stuck. Any schedule has the snapshots of this kind (fatality) is eliminated in the analysis. 12 schedules are eliminated due to the fatality risk.

For each snapshot 5 different fire locations are simulated, and 5 different ΔTs are obtained. ΔT is the difference between evacuation time of the scenarios with fire (RSET-WF) and without fire (RSET-WOF) for the same snapshot. Before determining one evacuation time for each snapshot the adjusted evacuation time is provided. In this part all the faster evacuations explained in Moniri Tokmehdash [27]'s report are assumed as zero. The reason is that $\Delta T<0$ cases are faster than the base line (The without fire case). The safest condition is assumed as the case of without fire, so that all the faster cases evacuation times are assumed safe and the ΔT is set as zero.

The next step is adding 5 different ΔTs of each snapshot to obtain the total ΔTs as $\Delta T'$ and multiplying it to the duration of that specific snapshot to calculate $FR_{Snapshot}$ (FR=Fire Risk). In each schedule all the $FR_{Snapshot}$ are added and the $FR'_{Schedule}$ is calculated as the factor of safety for analysis. All the equations associated with the calculation of Risk Factor are presented in Equation 2 to 5.

Equation 2. ΔT snapshots

$$\Delta T_{Snapshot} = RSET_{With-Fire} - RSET_{Without-Fire}$$

Equation 3. ΔT′

$$\Delta T' = \sum_{i=1}^{5} \Delta T_{Snapshot}$$

Equation 4. Fire Risk of snapshots

$$FR_{Snapshot} = \Delta T' \times Duration_{Snapshot}$$

Equation 5. Fire Risk of schedules

$$FR' = R_{Schedule} = \sum_{i=1}^{n} FR_{Snapshot}$$

In Table. 19 the whole procedure of creating risk factor as $FR'_{Snapshot}$ for 8th floor assigned to remaining schedules are illustrated.

Table 19. Fire Risk of schedules 8th floor

Schedule	From	To	Act1	Act2	Act3	Act4	Evacuation ΔT (RAW)					Evacuation ΔT (Adjusted)					Snapshot Duration	$\Delta T'$	$FR_{Snapshot}$	$FR'_{Schedule}$
18	19	22	B	D	I		178.00	58.00	38.00	25.00	0.00	178.00	58.00	38.00	25.00	0.00	4	299.00	1196	1196
20	19	22	A	D	I		152.00	46.00	40.00	28.00	0.00	152.00	46.00	40.00	28.00	0.00	4	266.00	1064	1064
22	17	18	B	E	G		162.00	57.00	27.00	12.00	0.00	162.00	57.00	27.00	12.00	0.00	2	258.00	516	1760
	19	22	B	D	G		187.00	64.00	35.00	25.00	0.00	187.00	64.00	35.00	25.00	0.00	4	311.00	1244	
24	19	22	A	D	G		156.00	36.00	33.00	34.00	-4.00	156.00	36.00	33.00	34.00	0.00	4	259.00	1036	1036

In Table. 20 the $FR'_{Snapshot}$ evacuations for the whole building assigned to the schedules are illustrated. In this section all the taken steps for the analysis of the 8th floor are applied on the whole building results. The cost and the time of the schedules are the same, the only difference is the evacuation time of the whole building. In this part the impact of vertical evacuation is evaluated.

Table 20. Fire Risk of schedules whole building

Schedule	From	To	Act1	Act2	Act3	Act4	Evacuation ΔT (RAW)					Evacuation ΔT (Adjusted)					Snapshot Duration	$\Delta T'$	$FR_{Snapshot}$	$FR'_{Schedule}$
18	19	22	B	D	I		80.70	-52.80	-3.50	33.00	-2.00	80.70	0.00	0.00	33.00	0.00	4	113.70	454.8	454.8
20	19	22	A	D	I		27.00	-69.00	3.00	16.00	1.00	27.00	0.00	3.00	16.00	1.00	4	47.00	188	188
22	17	18	B	E	G		47.30	-73.70	-15.20	-1.00	0.50	47.30	0.00	0.00	0.00	0.50	2	47.80	95.6	319.6
	19	22	B	D	G		56.00	-71.70	-4.00	-14.50	0.00	56.00	0.00	0.00	0.00	0.00	4	56.00	224	
24	19	22	A	D	G		33.00	-59.00	18.00	-2.00	4.00	33.00	0.00	18.00	0.00	4.00	4	55.00	220	220

5.1.3.3.2. Method B:

The fatalities and casualty cases are eliminated in the first step same as the method A. The maximum of 5 different ΔTs is selected as ΔT". The adjustment on ΔTs is applied with the same logic of method A. In each schedule the maximum ΔT" of different snapshots of the schedule is considered as the $FR"_{Schedule}$ (Fire Risk Factor). All the equations associated with the calculation of Risk Factor are presented in Equation 6 to 8.

Equation 6. ΔT

$$\Delta T_{Snapshot} = RSET_{With-Fire} - RSET_{Without-Fire}$$

Equation 7. ΔT"

$$\Delta T'' = Max(\Delta T_{Snapshot})$$

Equation 8. Fire Risk

$$FR'' = FR_{Schedule} = Max(\Delta T'')$$

In Table. 21 the whole procedure of creating risk factor as $FR"_{Snapshot}$ for 8th floor assigned to remaining schedules are illustrated.

Table 21. Fire Risk of schedules 8th floor

Schedule	From	To	Act1	Act2	Act3	Act4	Evacuation ΔT (RAW)					Evacuation ΔT (Adjusted)					ΔT"	$FR"_{Schedule}$
18	19	22	B	D	I		178.00	58.00	38.00	25.00	0.00	178.00	58.00	38.00	25.00	0.00	178	178
20	19	22	A	D	I		152.00	46.00	40.00	28.00	0.00	152.00	46.00	40.00	28.00	0.00	152	152
22	17	18	B	E	G		162.00	57.00	27.00	12.00	0.00	162.00	57.00	27.00	12.00	0.00	162	187
	19	22	B	D	G		187.00	64.00	35.00	25.00	0.00	187.00	64.00	35.00	25.00	0.00	187	
24	19	22	A	D	G		156.00	36.00	33.00	34.00	-4.00	156.00	36.00	33.00	34.00	0.00	156	156

In Table. 22 the $FR"_{Snapshot}$ evacuations for the whole building assigned to the schedules are illustrated.

Table 22. Fire Risk of schedules whole building

Schedule	From	To	Act1	Act2	Act3	Act4	Evacuation ΔT (RAW)					Evacuation ΔT (Adjusted)					ΔT"	$FR"_{Schedule}$
18	19	22	B	D	I		80.70	-52.80	-3.50	33.00	-2.00	80.70	0.00	0.00	33.00	0.00	80.7	80.7
20	19	22	A	D	I		27.00	-69.00	3.00	16.00	1.00	27.00	0.00	3.00	16.00	1.00	27	27
22	17	18	B	E	G		47.30	-73.70	-15.20	-1.00	0.50	47.30	0.00	0.00	0.00	0.50	47.3	56
	19	22	B	D	G		56.00	-71.70	-4.00	-14.50	0.00	56.00	0.00	0.00	0.00	0.00	56	
24	19	22	A	D	G		33.00	-59.00	18.00	-2.00	4.00	33.00	0.00	18.00	0.00	4.00	33	33

5.1.3.4. Time, Cost, and Safety Evaluation:

In the last part, all three elements of cost, time and safety are considered to evaluate the scenarios.

In terms of time, it is assumed that the renovation should not last longer than 60 days, 2 months. This assumption eliminates the first 16 out of 32 schedules from 1 crew- 1 crew alternatives, including 65 total days. The cashflow of each schedule has different associated mod cost, none of the schedules are eliminated in the matter of cost. In terms of safety all the fatality cases are eliminated. This elimination reduces all the remaining schedules from 16 to 4.

All the 4 schedules are acceptable in terms of cost, time, and safety.

The method of recommending one schedule out of all remaining schedules is presented in Equation 9, TCS is a number assigned to each schedule and the objective is to find the minimum TCS.

Equation 9. Time, cost, safety

$$TCS = Time \times Cost \times Safety$$

The 8th floor and the whole building have different fire safety factors. In this stage both factors are combined in two different methods. The first is by adding the safety factors of 8th floor and whole building (TCS sum) and the second is by multiplying them (TCS multiply). In each method, in terms of importance of these factors two approaches are implemented. In one approach both have the same ratio and in the other approach the 8th floor has 75% weight factor and the whole building has 25% weight factor. In the first approach the whole building evacuation and the 8th floor evacuation are considered with the same importance although in the second approach, the reason of higher weight factor for 8th floor is that the fire is happening in the 8th floor and the staircases are pressurized. As soon as the agents get into the staircases, they are safe.

The last step is to apply two methods including two approaches of safety on the 4 remaining schedules.

5.1.3.4.1. Method A:

In this method the Fire Risk factor is based on the firs safety evaluation method mentioned in section 5.2.1.3.1.

The final schedules are illustrated in Table. 23 and Table. 24 the first table is based on the 50 % weight factor for 8th floor and 50% weight factor for the whole building evacuation safety and the second table is based on the 75 % weight factor 8th floor and 25% weight factor whole building evacuation safety.

Table 23. Schedule Evaluation-Safety Method A- 50%-50% Importance

Schedule Evaluation-Safety Method A- 50%-50% Importance								
Schedule	**Duration**	**Cost**	**FR' 8th floor**	**FR' whole building**	**Sum FR' of 8th floor & whole buildinh**	**Multiply FR' of 8th floor & whole buildinh**	**TCS (sum)**	**TCS (Multiply)**
18	36	160	1196	454.8	1650.8	543940.8	9,508,608	3,133,099,008
20	36	160	1064	188	1252	200032	7,211,520	1,152,184,320
22	36	160	1760	319.6	2079.6	562496	11,978,496	3,239,976,960
24	36	160	1036	220	1256	227920	7,234,560	1,312,819,200

Table 24. Schedule Evaluation-Safety Method A- 75%-25% Importance

Schedule Evaluation-Safety Method A- 75%-25% Importance								
Schedule	**Duration**	**Cost**	**FR' 8th floor**	**FR' whole building**	**Sum FR' of 8th floor & whole buildinh**	**Multiply FR' of 8th floor & whole buildinh**	**TCS (sum)**	**TCS (Multiply)**
18	36	160	897	113.7	1010.7	101988.9	5,821,632	587,456,064
20	36	160	798	47	845	37506	4,867,200	216,034,560
22	36	160	1320	79.9	1399.9	105468	8063424	607,495,680
24	36	160	777	55	832	42735	4,792,320	246,153,600

5.1.3.4.2. Method B:

In this method the Fire Risk factor is based on the second method mentioned in section 5.2.1.3.2.

The final schedules are illustrated in Table. 25 and Table. 26. The first table is based on the 50 % weight factor 8th floor and 50% weight factor whole building evacuation safety and the second table is based on the 75 % weight factor 8th floor and 25% weight factor whole building evacuation safety.

Table 25. Schedule Evaluation-Safety Method B- 50%-50% Importance

Schedule Evaluation-Safety Method B- 50%-50% Importance								
Schedule	**Duration**	**Cost**	**FR" 8th floor**	**FR" whole building floor**	**Sum FR" of 8th floor & whole buildinh**	**Multiply FR" of 8th floor & whole buildinh**	**TCS (sum)**	**TCS (Multiply)**
18	36	160	178	80.7	258.7	14364.6	1,490,112	82,740,096
20	36	160	152	27	179	4104	1,031,040	23,639,040
22	36	160	187	56	243	10472	1,399,680	60,318,720
24	36	160	156	33	189	5148	1,088,640	29,652,480

Table 26. Schedule Evaluation-Safety Method B- 75%-25% Importance

Schedule Evaluation-Safety Method B- 75%-25% Importance								
Schedule	**Duration**	**Cost**	**FR" 8th floor**	**FR" whole building floor**	**Sum FR" of 8th floor & whole buildinh**	**Multiply FR" of 8th floor & whole buildinh**	**TCS (sum)**	**TCS (Multiply)**
18	36	160	133.5	20.175	153.675	2693.3625	885,168	15,513,768
20	36	160	114	6.75	120.75	769.5	695,520	4,432,320
22	36	160	140.25	14	154.25	1963.5	888,480	11,309,760
24	36	160	117	8.25	125.25	965.25	721,440	5,559,840

5.2. Discussion

The schedule with the minimum TCS is the nominated schedule. In 7 out of 8 analysis the recommended schedule is schedule No. 20 including the snapshots of A-D-I. Schedule No. 20 is presented in Fig. 22.

	Activity	No. of Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Sch-20	B	15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1																					
	A	14																1	1	1	1	1	1	1	1	1	1	1	1	1	1							
	F	8	2	2	2	2	2	2	2	2																												
	E	10									2	2	2	2	2	2	2	2	2	2																		
	D	7																			2	2	2	2	2	2	2											
	C	11																										2	2	2	2	2	2	2	2	2	2	2
	G	6	3	3	3	3	3	3																														
	H	6							3	3	3	3	3	3																								
	I	10													3	3	3	3	3	3	3	3	3	3														

Figure 22. Schedule No.20

The highlighted period is the duration that the schedule has the A-D-I snapshot. In this snapshot 2 crews are operating in the labs and 1 crew is operating in the corridors. Crew 1 is responsible for labs B and A. Crew 2 is operating at F-E-D-C labs with respect to the order. G - H and I corridors are operating by crew number 3.

The only analysis that has a different result is schedule evaluation of Method A considering 75% weight factor for the 8th floor. The nominated schedule in this analysis is schedule No.24. This schedule is illustrated in Fig. 23.

	Activity	No. of Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Sch-24	B	15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1																					
	A	14																1	1	1	1	1	1	1	1	1	1	1	1	1	1							
	F	8	2	2	2	2	2	2	2	2																												
	E	10									2	2	2	2	2	2	2	2	2	2																		
	D	7																			2	2	2	2	2	2	2											
	C	11																										2	2	2	2	2	2	2	2	2	2	2
	I	10	3	3	3	3	3	3	3	3	3	3																										
	H	6											3	3	3	3	3	3																				
	G	6																	3	3	3	3	3	3														

Figure 23. Schedule No.24

The highlighted period is the duration that the schedule has the A-D-G snapshot. In this snapshot 2 crews are operating in the labs and 1 crew is operating in the corridors. Crew 1 is responsible for labs B and A. Crew 2 is operating at F-E-D-C labs with respect to the order. I-H and G corridors are operating by crew number 3. The snapshot of A-D-G has one anomaly case in fire evacuation simulation. The with fire scenario is faster than without fire scenario when the fire is in front of spiral. This anomaly is explained by detail in Moniri Tokmehdash [27]'s report. This case requires further investigation. The other remaining schedules do not have any anomaly cases.

The results show that the 1 crew- 1 crew alternatives are eliminated due to the time metric. 2 crews-2 crews are all eliminated due to the fatality risk. The remaining 4 schedules are from 2 crews- 1 crew alternative. Both nominated schedules consist of the combination of 2 labs of A and D.

6. Conclusion, Limitations, and Future Works

This study developed a framework to investigate the effect of occupant's safety as an additional decision criterion, on the construction schedules. To implement this investigation, the building examination provides the basic information such as the area of the building, number of rooms, exist doors, connections such as corridors, etc. All the possible construction scenario combinations are obtained based on the building information and assumptions. In the next step construction and operation logics are applied on the possible construction combinations. Scheduling is the next step considering the remaining construction activity combinations. The construction schedules and number of occupants of the building, are used in the evacuation modelling. The fire is molded in Pyrosim (FDS Fire simulator) by importing The 3D model of the building in a BIM based environment. By integration of Pyrosim and Pathfinder (Agent based modelling) two RSETs (Required safe exit time) are obtained. The first RSET is based on the scenario without fire and the second RSET is the scenario with fire. The difference between these two numbers provide an indicator of risk. The greater this number is the fire risk of that snapshot is higher. Each schedule has an indicator of cost which is obtained from cashflow. All the schedules have durations as will. After schedule elimination of Fatality cases in the safety and duration required in the time section, the remaining schedules are acceptable in terms of cost, time and safety. Two methods are applied to nominate one of the schedules. 88% of the results nominate the same schedule.

It is worth mentioning that the recommended schedules before considering the safety and evacuation time of the building was schedule 17 to schedule 32. It means 16 schedules in terms of cost and time was acceptable. After considering the safety, 12 out of 16 schedules had the possibility of fatalities and casualties. This proves the necessity of considering safety in construction planning stage. The result suggests 4 schedules out of 32 and out of four remaining one is nominated.

The limitation of construction scheduling in this study is that only three activity combination alternatives are assumed, in the process of generation of schedules other possible activity combinations can be considered in future studies. Regarding the renovation work and crew types, other possibilities also could be considered. In the final schedule evaluation process, other methods for time, cost, and safety can be considered as well.

The limitation of evacuation modeling, is not having access to the as-built drawings of the building. This reduces the accuracy of the result. The actual number of occupants is not considered, and the calculations are based on the building codes. The gender and the age of the occupants are based on the assumptions. The speed of different genders and ages vary in the pathfinder. Simulation based on the more realistic scenarios, makes the result more accurate. It is recommended in future studies, to simulate the evacuation based on the actual gender and age distribution in the building. In the occupancy calculation, instead of 50% capacity of the spaces, the max capacity also can be tested. Disabled occupants and people requiring assistance are not considered, modeling the disable people can be more investigated in future studies.

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