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Impact of Fire on Occupants' Evacuation in Projects Under Construction Renovation

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Abstract

Safety is one the important goals in any construction projects. In construction sites fire has high potential of occurrence as a safety thread due to the presence of combustible materials, hot work, and negligence of crew. When this fire hazards come to a construction renovation of building under operation, could affect evacuation of people and cause more severe consequences such as occupants' injuries and deaths. Because the space is shared between construction and occupants. Therefore, this study proposes a framework consists of co-simulation of fire and evacuation with integration of BIM based environment, Pyrosim (FDS) and Pathfinder (ABM simulator) software tools, to investigate the impact of fire on the evacuation of occupants under construction renovation works. This framework was used for Concordia University's EV Building as a case study. Results showed that fire in almost 60% of all cases increased the evacuation time for 15.5% in the entire building and 168% for 8th floor in the most severe cases.

1. Introduction

In any construction project the primary goal is to deliver a high-quality product on time and on budget while providing a safe work environment for the construction workers and the occupants alike. Potential hazards that could affect workplace safety include, but are not limited to, lack of fall protection, failure in electrical equipment, workers' negligence, unsupervised hot works, scaffolding collapse, failure to use proper personal protective equipment, and many others [1]. Some of these come with more severe consequences. For example, a cigarette or hot work close to combustibles on a construction site is a potential ignition source that can cause fire in varying intensities. Fire can cause civilian deaths and injuries and can also bring cost overruns and project delays. According to the US National Fire Protection Association (NFPA), the local fire departments reported that the construction industry had an average of 3,840 and 2,580 fire incidents per year involving structures that were either under construction or under renovations, respectively. These fires collectively caused 12 civilian deaths, 101 civilian injuries, and $408 million damage in direct property annually between 2013 and 2017 [2].

Construction renovation projects in occupied buildings make construction planning more complex and challenging since it must consider safety of both workers and the occupants, occupants' reallocation and cost effectiveness of the project due to the presence of occupants, workers, and possible combustibles in the building. According to the Canadian Fire Safety Association (CFSA) report published in 2014, the Ontario Fire Marshal (OFM) reported that the total number of fire incidents for all occupancy types in occupied buildings under renovation was five times higher compared to new buildings under construction. In addition, between 2008 and 2013, fires in renovation projects had increased, although total number of fires dropped [3]. Furthermore, in high-rise buildings, additional vertical fire growth could make the situation even more severe due to the possibility of higher number of injuries and fatalities [4].

The above data show the importance of fire related safety planning in occupied high-rise buildings undergoing construction renovation that may not otherwise have conducted necessary safety assessment and fire risk mitigation analyses. Such studies must be done as part of the initial planning process. The question is that during the preliminary project planning process, how authorities can prevent or decrease the fire incidents risk, which would save lives, time, and cost during the project implementation.

To explore possible solutions for these concerns, one of the main requirements is to obtain information regarding occupants' behavior, and evacuation time through records of occupants' evacuation in a fire emergency. However, it is not possible to obtain such data with actual evacuation during an emergency, specifically in the presence of fire. One of the most useful and effective approaches is to use the available fire and evacuation simulator software tools developed by engineers, to facilitate access to the desired data and evacuation process [5].

This research paper, with the aid of previous studies and utilization of modern tools, will attempt to conduct a co-simulation framework consists of fire and evacuation related to a construction renovation scenario.

This work has been in parallel coordination with another ongoing study [6], and the two reports cross-reference one another.

2. Literature Review

2.1. Fire Modeling, Simulation, and Analysis

Having a safe building in terms of fire safety requires an analysis of both fire and evacuation separately and together. Modeling and simulation of fire can be implemented in different ways. The first approach is only considering the impact of fire on exit doors closure. G. N. et al. [7] in their study investigated the impact of such closure probability of exit doors on safe exit evacuation time on the 10th floor of USCI University. The results show the importance of fire location in front of the exit door and linear correlation of the number of blocked doors with the number of remaining occupants in an evacuation. Lack of fire simulation brings a gap in fire and evacuation modeling regarding the impact of fire and its byproducts such as toxic gases and visibility reduction on evacuees' behavior and corresponding impact on evacuation time [7].

The second approach, simulating fire, is possible through a tool called Fire Dynamic Simulator (FDS) which is considered as one of the popular and acceptable approaches in the fire engineering industry. This tool is developed by the National Institute of Standards and Technology (NIST). FDS simulates a fire model by calculating and solving numerically using many Navier-Stokes NIST-equations appropriate for low-speed flow. In addition, this tool provides operators with modeling facilities' geometry, objects, materials, and fire properties in a programming-based environment, which is hard to work with. Moreover, simulation results will be obtained in 2D (plot time history results and slices) and 3D (visual smoke view videos) [8], [9].

Based on FDS user guide, to simulate a solid, which is made by surface, material and its governing reaction should be defined. Defining materials includes associated thermal properties and pyrolysis behavior [8]. Most common way to define material's pyrolysis is specifying it as burner surface with its associated heat release rate per unit of area (HRRPUA) and assigning the related reaction to that specific material. This HRRPUA can be defined as a fixed number or ramping-up by time through pre-defined or user-defined functions during the simulation [8], [9]. Cao et al. [5] modeled different fire scenarios in a 12x12m room under fire emergency with the aid of FDS. In their scenarios, they assumed different fire intensities by changing the material type and its heat release rate in simulations as a fixed number. Considered materials in this study were wood as raw material of furniture and polystyrene as wall insulation foam due to their popularity, which have different soot and Carbon monoxide (CO) yield in associated reaction with them. In addition, various HRRPUA are modeled from 500 kw/m2 to 5000 kw/m2. The fire results show that the material with higher soot amount and HRRPUA creates more and faster soot products and increasing in temperature [5]. However, Wei and Wang [10] used another approach, t-squared pre-defined function for defining HRRPUA. This approach provides practitioner with assigning growth rate for ramp-up of HRRPUA [10]. The appropriate method for choosing this set up is based on the material under investigation which should be tested by methods like Cone-Colorimeter for the real HRR curve [11].

Working with FDS and its programming interface is challenging since the operator does not have any visualization of the modeled geometry during the preparation process, specifically for complex geometries. The entire process of geometry modeling should be done by inputting X, Y, and Z coordinates of object [8], [12]. Regarding this issue, there are some studies that modeled their facility's geometry and fire in a visual-based FDS tool. **Li** et al. [13] in their study, with aid of Pyrosim software, modeled a possible fire incident in the university library in Nanjing, China to estimate the risk time associated with fire. This tool uses FDS as fire simulation engine in a Graphical User Interface (GUI). This graphical environment is facilitated geometry modeling and parameter definition process and serves as a new era for fire engineers to use FDS tool in a user friendly visual-based tool due to its complex nature. Their model includes two specific spaces (reading room and atrium) due to their importance regarding density of people and existence of combustible materials, respectively. Moreover, they added four different types of devices which is a feature of both FDS and Pyrosim. These devices are set for the measurement of height, temperature, and CO concentration of smoke and visibility reduction. Extracted results from these devices help the analysis of fire impact on evacuees. By analyzing the results, they found that when smoke reaches to 2m height from the floor surface, the smoke layer is considered critical and risky [9], [12], [13].

While modeling in Pyrosim is a lot easier compared to the FDS tool, for more geometry's details and complexity like curves and components' material type would be more difficult to model. Regarding proposed challenge, Pyrosim supports different file extensions such as DWG, DXF, FBX, and IFC which provides interoperability between FDS and BIM as a product by importing ready semantic models from 3D modeling software tools such as Autodesk Revit into FDS [9]. Wang et al. [14], with aid of this feature, imported their architectural model which was modeled in Revit tool with a level of detail (LOD) 200 and DWG extension into Pyrosim. LOD 200 includes geometric data of building components (beam, column, slab, window, and many other major components) such as size, shape, and orientation [14]. However, Sun and Turkan [12], imported the 3D model created by Revit with LOD 300 and DXF extension, which not only contains geometric information but also includes material type of components. This information makes software possible to group building materials and components automatically and ready for defining material thermal properties [12].

In terms of measuring the impact of fire on evacuation, there are different approaches, two of which were mentioned before. Regarding second approach, modeling the fire in fire simulation software tools, all of the studies in this literature used the same concept for evaluating the impact of fire on evacuation but with different constraints. This concept is based on two parameters; available safe egress time (ASET) and required safe egress time (RSET). In simple words, ASET is the time of danger due to fire or its byproducts which is calculated by FDS or Pyrosim. On the other hand, RSET is the time of reaching to a safe area for evacuees and it is calculated by code-based hand calculations or evacuation simulator such as Anylogic, Pathfinder, and STEPS. As long as RSET is less than ASET, safe evacuation could be expected based on simulations. ASET can be calculated based on different constraints [10], [12]–[14]. Wei and Wang [10] estimated the danger time only by considering 2m flu gas height factor, which is assumed from the floor ground [10]. However, Wang et al. [14] instead of defining one parameter, used multiple parameters based on Safe Fire Protective Engineering (SFPE) handbook. This handbook provides three tolerance limits for agents, temperature more than 60 °C, concentration of carbon monoxide higher than 1400 ppm, and visibility less than 2m. As mentioned earlier, by setting multiple devices in the fire model the numbers associated with these parameters can be calculated. After obtaining the devices' records form simulation, the minimum time to reach any of mentioned hazard parameters considered as ASET, which in this study visibility less than 2m was considered effective [14]. Furthermore, **Li et al.** [13], expanded list of tolerance limits by adding Fractional Effective Does (FED) parameter in their investigation. They considered a building unsafe if evacuation time exceeded RSET in which FED value is 0.1 [13]. Implementation of this parameter is based on the equations of SFPE Handbook of Fire Protection Engineering and focus of that is on concentration of narcotic gases CO, CO2, and O2 [15]. In these two studies, only one level of risk associated with fire was defined which does not show other stages of the evacuation where it involves injured occupants [13]. Sun and Turkan [12], with respect to the SFPE Handbook tolerance limits, provided three stages for ASET. First and second stages are defined based on the height of the smoke layer when it reaches 1.5 m and 1.2 m from the floor level, respectively. Last stage assigned to a condition in which one of the fire reaction byproducts (heat, toxic gases, and smoke density) reaches human physical tolerance. After running simulation, ASET stages from first to third are considered as uninjured escape, injured escape without death, and failure escape alive, respectively [12].

Based on the previous studies Pyrosim is selected for fire modeling and simulation. In addition, in terms of evaluation the impact of fire on evacuation time, because of the co-simulation feature of pathfinder, REST for with and without fire scenarios will be calculated instead of calculation of ASET [6].

3. Methodology

To evaluate the impact of fire on evacuation of a building under construction renovation, this study is proposing a framework comprised of 5 different main steps: 1) Building examination, 2) Construction Planning, 3) Fire scenario generation and modeling, 4) Evacuation modeling and Co-Simulation, and 5) Co-Simulation result evaluation which are illustrated in Fig.1.

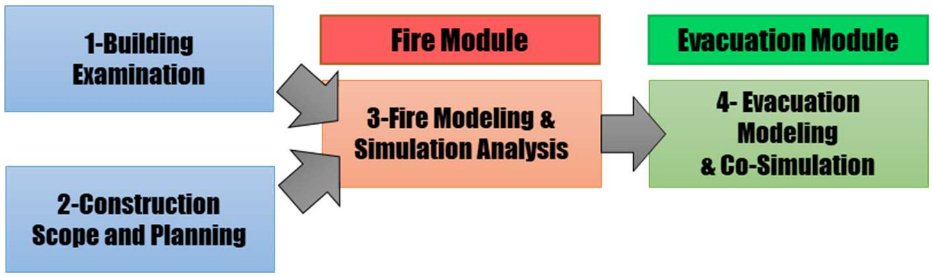


Figure 1. Evaluation Framework of Fire on Evacuation

As shown in Fig. 1, the first step is **Building Examination**. BIM model is used to examine the building for extracting the information related to the floors' layout, number and location of pressurized exit doors and regular stairs, components' material, and fire zones. Before proceeding into the third step, from the second step – **Construction Scope and Planning** – which is done by the planner [6], only 2 outputs of that are required, 1) renovations' types and locations, 2) Final construction snapshots.

The third step, which is also named as Fire Module, is divided into 3 sections. First, by having the output of 2 previous steps, and according to the previous studies – Fire locations in front of exit doors are deemed more critical – the fire scenarios, including fire locations and intensities, are created. Second, the generated fires are modeled in the Pyrosim software tool through the following steps: a) Importing Revit model for the purpose of building geometry, b) Defining meshes, c) Defining reaction, d) Defining fire ignition source by creating obstruction, material and burner surfaces, e) Defining 2D slices for extracting the fire result, f) Setting up the output of fire simulation for the Co-Simulation because it allows the Pathfinder software tool has access to the fire results. Third, by choosing the simulation time, the fire models are ready to be run. The obtained results are Pyrosim file (.psm) and smoke view file (.smv) which are required for Evacuation Modeling and Co-Simulation. All the process of Fire Module is illustrated in the Fig. 2.

In the fourth step, which is also named as Evacuation Module, by having the obtained results from Building Examination (occupants' number and distribution and building layout), Construction Scope and Planning (final construction snapshots), and Fire Module (different fire scenarios), evacuation models for each snapshot with and without the impact of fire are generated. After running the Co-Simulations for all generated models, the evacuation time with and without the impact of fire are obtained. This fourth step is explained in detail by Shams Abadi in her report [6].

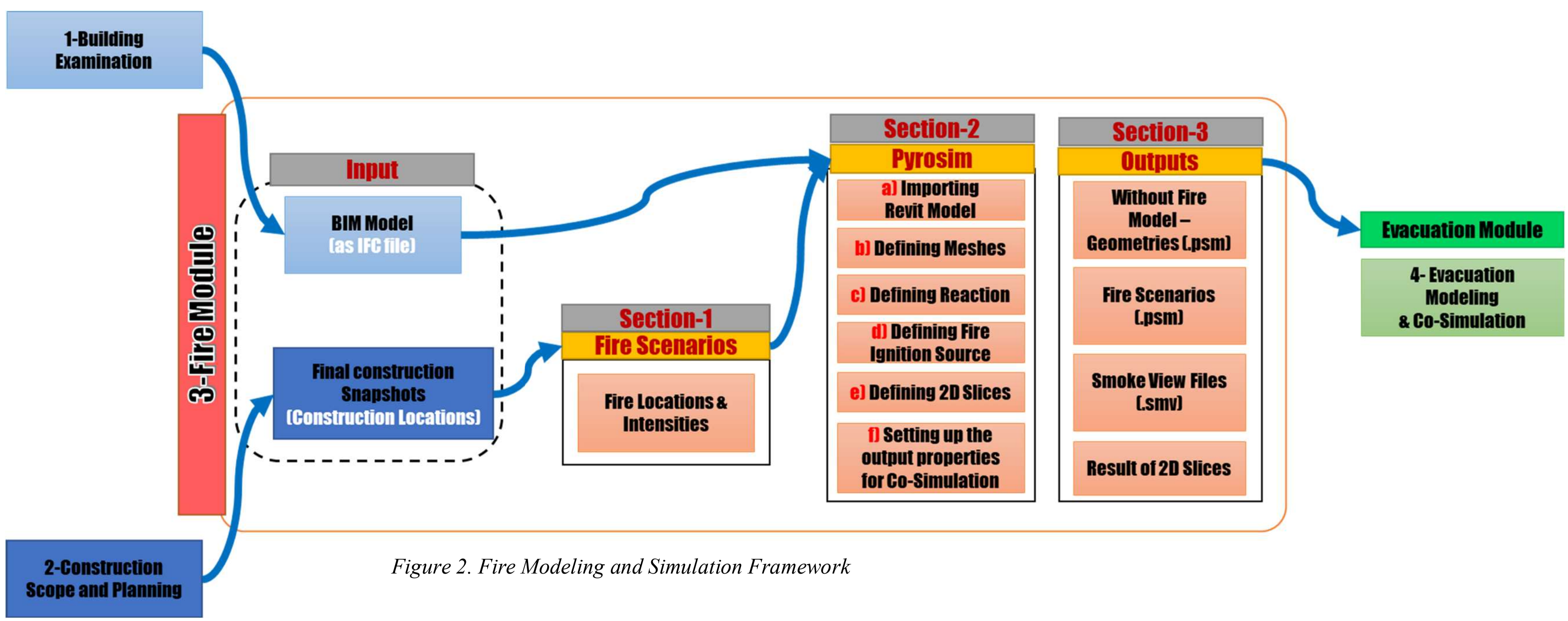


Figure 2. Fire Modeling and Simulation Framework

4. Case Study

4.1. Building Examination

The Engineering, Computer Science, and Visual Arts complex (EV Building) of Concordia University is chosen as the case study for this research. The EV Building is located in downtown Montreal, Canada and was opened in September 2005. The EV Building is comprised of two 17-storey towers, which are connected through indoor common corridors and include administrative offices, the Dean's Office, over 300 specialized labs, conference and meeting rooms, and student common areas. In a normal situation, EV Building has an average of 1,000 occupants per day and operates 24 hours, 7 days a week. Because of the COVID-19 guidelines, the university is partially open to students and staff with limited access [16]. Based on the obtained 3D model of 9^{th} floor and Covid-19 circumstances, the same layout of 9^{th} floor is considered for the entire building due to lack of access to the University's as-built plans. As it is shown in Fig. 3, this layout is divided into 2 parts: on the bottom Engineering part (E-Part) and on top Visual Arts part (V-Part). Based on the obtained model, it is considered that each floor includes 6 Visual Arts laboratories, 35 student offices, 9 staff offices, 1 kitchenet, 4 bathrooms, 8 elevators, 4 pressurized exit doors, and 2 regular staircases that are connected through a corridor. Of the two staircases, the one on the E-Part, is a spiral staircase connecting 3 floors. According to the fire design of Concordia EV building, all 3 floors are considered as a fire zone, which indicates fire and smoke cannot travel to other floors and will be trapped in the that fire zone.

Figure 3. EV-Building, 9th floor layout

4.2. Construction Scope and Planning

As explained in Shams Abadi's report [6], after selecting ceiling and duct work in the labs and corridors as renovations' types and locations respectively, the possible activities combination are determined. After that by considering construction and operational logics, some of combinations are eliminated. Additionally, the duration of each activity is estimated based on the crew types properties (daily output and crew members) which are specified by the selected renovation type from RSMeans Data base. Then by selecting the crew combination for the selected activities, different schedules and associated construction snapshots are generated. Then, these snapshots are filtered by redundancy and possibility of occupant's reallocation factors. At the end of this process, 18 construction snapshots are remained which are final construction snapshots[6].

4.3. Fire Scenarios

Before start of modeling, fire scenarios including fire locations and intensities should be set. In this research, choosing a fire scenario is comprised of two steps. First, per section 4.1, each floor has four pressurized exit doors and two staircases one in the V-part and another in E-part. The one in the E-part is a spiral staircase, which is an indoor void space connecting three floors as a fire zone. Based on the regulations of Concordia **University Fire Marshal**, none of the spiral and regular staircases can be used during the evacuation [17]. They consider these two staircases as chimneys since both are unpressurized and smoke travels through them causing injuries or death to people evacuating through them. As mentioned in the Methodology, one of the critical locations for fire occurrence is in front of exit doors. Therefore, four out of five fire locations are assumed in front of each pressurized exit doors and the last location is assumed in front of the spiral staircase. The importance of spiral staircase fire is that this research paper simulates both horizontal and vertical fire. The special location of spiral staircase can bring the chimney effect to this simulation and let smoke travel to upper floors from the start of the simulation. As such, this research considered 5 fire locations per each snapshot as shown in the Fig. 4. Snapshots are extracted from Construction Planning report [6].

After choosing the fire locations, the intensity of fires is the second important step. It is assumed that each fire, based on the location of the construction sites in each snapshot, can be categorized as high or low intensity. If the fire is in or close to the construction site, it is considered a high intensity fire due to the presence of hot works and combustibles. Otherwise, it is considered a low intensity fire. The only exception is the fire for spiral staircase, which is assumed to be high intensity for having the chimney effect. Based on these assumptions and final snapshots, fires in front of exit doors 3 and 4 are always low intensity because no renovation is considered in those corridors or offices. In addition, fires in front of doors 1 and 2 can have low or high intensity based on the snapshot under simulation. Thus, a total of 7 fires will be modeled as shown in Table. 1.

Table 1. Seven fires based on intensity

No.	Fire Location	Intensity
1	Exit-Door-01	High
2	Exit-Door-01	Low
3	Exit-Door-02	High
4	Exit-Door-02	Low
5	Exit-Door-03	Low
6	Exit-Door-04	Low
7	Spiral	High

Figure 4. Five fire locations per each snapshot

4.4. Modeling Assumptions

According to section 4.1. – Building Examination – in fire design of Concordia EV building, all 3 floors are considered as a fire zone which means fire and smoke cannot travel to other floors and will be trapped in the fire zone. Therefore, only one fire zone is modeled in this research, which is comprised of floors 8, 9, and 10. Another reason for this selection is the investigation of fire impact on upper floors in the evacuation process. Also, only the common areas are considered for the fire modeling.

4.5. Fire Modeling Steps (Pyrosim)

This section is divided into six steps starting with importing Revit model, then continues by defining meshes, reaction, and fire ignition source. At the end, it is finished by setting up the output properties, slices and running the analysis.

The fire modeling process was done on a laptop with an Intel dual-core i5 processor (2.5 GHz) with 8 GB available RAM and the simulations were run on a computer with an Intel quad-core Xenon processor E5 v5 family with 32 GB RAM.

4.5.1. Importing Revit Model

As mentioned in the Literature Review section, although Pyrosim has the feature for geometry modeling, working with drawing tools for complex and large models is not easy. But with the feature of supporting different file extensions (IFC, DWG, DXF, and FBX), all modeling can be done in 3D modeling software tools such as Autodesk Revit and then be imported into the Pyrosim. In this research, the EV Building comprised of 16 floors is modeled in Revit based on the 9th floor model with LOD 300, then exported as IFC Version 4 Reference View. It is important to mention that as proposed in section 3.3.2., only 3 floors (8th, 9th, and 10th) are imported in Pyrosim. The reason for using this extension rather than other supported extensions by Pyrosim such as DWG, DXF, and FBX is that after importing these extensions into Pyrosim, the model's information comes partially. Specifically, components' material types are missing. In addition, among different options of IFC, Reference View is chosen because while the Design Transfer View is more comprehensive, in the process of importing the file into the Pyrosim, the software tool crashed. Imported geometry is shown in Fig. 5.

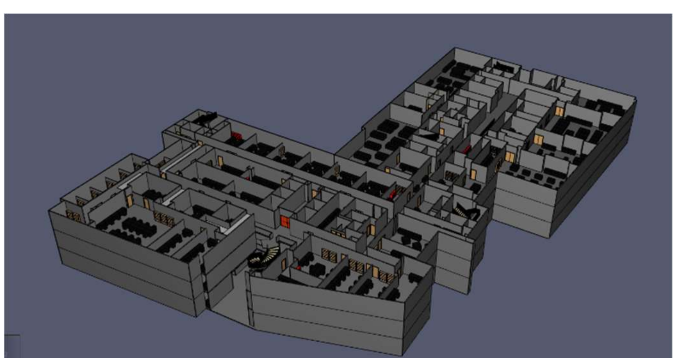


Figure 5. Pyrosim geometry of 8th, 9th, and 10th floors

4.5.2. Defining Meshes

After importing the geometry, first meshes should be defined. Meshes are the domain of FDS calculations in the process of analysis and they are defined by mesh boundaries and cell sizes. Any object outside of mesh boundaries does not appear in the results, therefore, it is important to cover all of the desired geometry parts with meshes for the simulation analysis. In terms of boundary definition, by inputting $X_{1,2}$, $Y_{1,2}$, $Z_{1,2}$ coordinates rectangular prism volume of the desired mesh will be created. Another important parameter is cell size. Each mesh comprised of multiple rectangular cells and the information of FDS calculations is transferred by these cells, from one cell to another. The smaller the mesh size has a higher resolution. But the smaller and higher number of cells bring a huge volume of computation into the analysis, so the boundary and cell size selection is very important[8], [9].

In this study, for easing the pressure of heavy analysis, meshes are only considered in the common areas (corridors and common spaces). Also, instead of having one big mesh, they are divided into smaller parts comprised of 13 meshes with overall number of 760,368 cells with 0.25m size for each cell. Cell size is normally estimated through the provided calculator on Thunderhead Engineering website, which is based on FDS User Manual's instruction. This calculator estimates the cell size based on HRR of fire, density and specific heat of material, ambient temperature, and gravity. But in this study, because of the complexity of finding a proper cell size, after consultation with a fire engineer, it is considered as 0.25m [18]. The overall form of the modeled mesh is shown in Fig. 6.

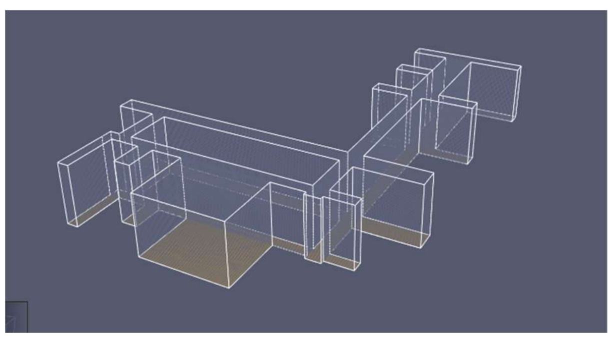


Figure 6. Pyrosim mesh domain

Another consideration in mesh modeling for the purpose of faster analysis is assigning a group of meshes to separate cores of Computer processor. In section 6.3 of FDS User Manual, it is explained that using advanced option of mesh properties, the configuration will be applied to the model [8]. This technique saves a lot of time in the analysis time.

The very last step of mesh modeling is setting mesh boundaries as open vent otherwise, the designed mesh will stay as a sealed box and air pressure will rise due to the heat of fire, and fire will eventually be extinguished due to the lack of air. Thus, in this model, all the boundary's face set as open vent except faces on top and bottom elevation.

4.5.3. Defining Reaction

Reaction is another important parameter that is directly related to the material source. The reaction in FDS defines fuel, products, and heat of combustion [9]. In this study, based on the selected renovation types, Nylon is considered part of construction waste for material source for fire and is added to the fire model from the existing library of Pyrosim. The reaction properties are based on the SFPE Handbook of Fire Engineering Protection [11]. This reaction is simple chemistry (Fig. 7) which fuels properties that are comprised of H, N, O, and C after reacting with oxygen form multiple byproducts such as CO2, CO, Soot, N2, and H2O (Fig. 8) [9]. The reason for choosing Nylon instead of other combustibles is the high amount of soot yield in its reaction compared to other materials in the renovation site. As it is mentioned in Evacuation Modeling by Shams Abadi[6], the only reason behind the evaluation of materials based on the soot yield is because smoke is the only byproduct of fire which has impact on agents in Pathfinder. It means that the Pathfinder can only consider the visibility deduction impact on agents due to exposure to smoke.

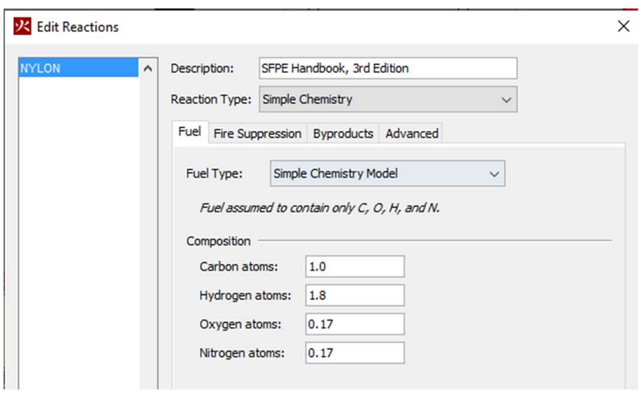


Figure 7. Nylon fuel properties

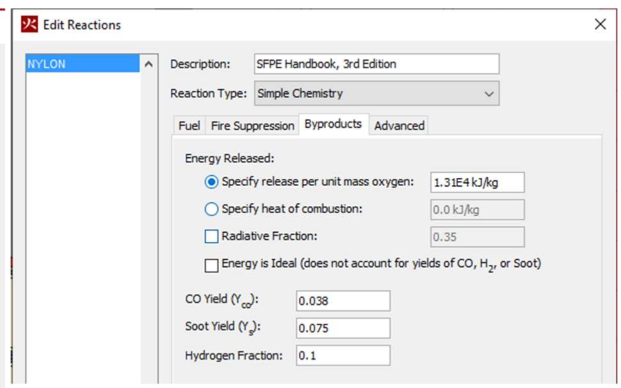


Figure 8. Nylon byproducts

4.5.4. Defining Fire Ignition Source

In general, modeling a fire ignition source by FDS includes three steps, (1) creating obstruction, (2) creating material surface, and (3) creating a burner surface. For modeling an object with associated material, obstruction and its material surface are created separately and then the created surface is assigned to the burner surface. With the aid of IFC extension, for defining the geometry's component materials of a complex model, all the materials of the Revit model are defined as different surfaces and only thermal properties should be defined. After that for ignition source again another surface is created but this time as burner not material. This burner surface is assigned to one the obstruction faces. This burner with a specified HRRPUA as fixed or ramp-up type, increase the temperature of the obstruction surface up to the ignition temperature then fire is created [9]. In addition, by applying the first two steps of the mentioned process on a complete imported geometry, fire propagation is modeled. This setting is time consuming in analysis process and computationally expensive because it significantly increases the simulation time which requires multiple computers for faster analysis.

In this study, for multiple reasons, only a burner surface with fixed HRRPUA on a vent instead of material surface on obstruction surface is considered and defining geometry's material components for fire propagation is eliminated. Normally, it takes a specific time for fire to reach to its defined HRRPUA value in the burner surface properties and, based on the burning material, if no combustible added to the fire, it will be extinguished. Ramp-up option gives users to simulate this situation. On the other hand, setting the HRRPUA as a fixed value removes the delay for reaching its defined value. In this case, HRRPUA is at the defined value from the beginning, and will sustain it to the end of predefined simulation time, which is specified by the user. As mentioned in Shams Abadi's [6] report, in the evacuation process of this study, reaction and detection times are not considered. This allows for the immediate evacuation of occupants, which means before the fire reaches to the detectors, alarms start operating where people are already aware of the fire. As such, at the beginning of the evacuation HRRPUA is not zero and reaches its defined value. Therefore, the best modeling option for this case is fixed HRRPUA [8], [11].

In modeling of fire propagation –defining surface material for different components and setting ignition temperature for each material– ignition source starts the fire and during its reaction temperature reaches nearby components. Each component, based on the ignition temperature of its material, starts burning. Once the combustible mass for ignition source is finished, there are still other burning materials, but as it is mentioned, this simulation is computationally time consuming. Although in the fire model of this study propagation of fire with this approach is eliminated, by fixing the HRRPUA of applied burner surface to a vent, there is a possibility to have the fire source up to the end of any defined simulation time[19]. In modeling a fire, a vent in FDS pumps out fuel which will ignite if it mixes with air. In addition, the size of this vent is important because it has direct impact on selecting the value of HRRPUA.

Based on the chosen fire intensities – low and high – in this modeling, 1000 KW/m^2 and 500 KW/m^2 are assigned to high and low values for HRRPUA of burner surface as a fixed number, respectively. The area of the vent on obstruction is considered 5 m^2 which is obtained by multiplying 1.5 m (vent width) by 3.33 m (vent length).

4.5.5. Defining 2D Slices and Setup Output Properties for Co-Simulation

After completing the model creation, the simulation parameters and output properties are the next steps. In terms of simulation output, due to the utilization of new feature of pathfinder – slowing down agents by smoke –as a part of this study, there is a special setting to prepare the Pyrosim results for importing into Pathfinder. Normally, to have fire results such as byproducts yield and temperature records, slices and devices should be modeled but when the results are being prepared for Pathfinder, there is no need for defining any slices or devices. By activating the Plot3D data in the result properties, all required results will be recorded in 3D [20].

However, for the purpose of obtaining information regarding the smoke spreading's behavior and visibility variation, in all fire models, a 2D soot visibility slice is defined. This slice is located only on the 8^{th} floor's meshes and it is set at height of 1.8m from the floor level which is selected based on the assumed height of the agents in the evacuation modeling.

4.5.6. Simulation Parameters and Running the Analysis (Output)

Regarding simulation parameters, everything is kept as default except for the simulation start and end time, which is adjusted to 0 sec to 300 sec, respectively.

In the last step, as all the meshes assigned to different cores of computer's processor, instead of using regular FDS analysis, FDS parallel analysis is selected.

The output of each fire simulation is one Pyrosim file (.psm) and one smoke view file (.smv). Both serve as input for the evacuation modeling in Pathfinder. Table. 2 shows the simulation and Analysis of all seven fires. The smoke view file also includes the visual results of defined slices.

Table 2. Pyrosim analysis times

No.	Fire Location	Intensity	Simulation Time (sec)	Analysis Time (sec)
1	Exit-Door-01	High	300	11 hours, 40 minutes, 13 seconds
2	Exit-Door-01	Low	300	9 hours, 17 minutes, 9 seconds
3	Exit-Door-02	High	300	12 hours, 49 minutes, 11 seconds
4	Exit-Door-02	Low	300	10 hours, 41 minutes, 42 seconds
5	Exit-Door-03	Low	300	7 hours, 41 minutes, 33 seconds
6	Exit-Door-04	Low	300	9 hours, 3 minutes, 40 seconds
7	Spiral	High	300	12 hours, 19 minutes, 23 seconds

4.6. Summary of Construction Scenarios and co-simulation

According to Shams Abadi's [6] Methodology referenced in the Construction Planning section, at the end of the process, 18 snapshots are nominated, and 5 fires based on renovation locations among 7 assumed locations – based on the section 4.3 Fire Scenario – are assigned to each snapshot, which are form 90 snapshots. For the purpose of co-simulation, a total of 90 snapshots with their associated fires plus 18 snapshots without fire are modeled and simulated in Pathfinder. Snapshots without fire are assumed safe and normal evacuation which are required for comparison with snapshots impacted by fire in the further steps.

5. Result and Discussion

5.1. Results

After running the co-simulation (Fire and Evacuation), as Shams Abadi [6] explained, the evacuation time of the entire building and 8th floor for 90 snapshots with fire plus 18 snapshots without fire are obtained.

5.1.1. Whole Building Result

The time of complete evacuation of the whole building is determined as the last second, the last occupant is evacuating from the exit door of ground floor. Two different situations are simulated for the whole building, which is 18 snapshots evacuation without the impact of fire, and 90 evacuation scenarios affected by the impact of smoke. The result shows the evacuation time of the whole building in 18 snapshots varies from 466.5 to 546 seconds (Fig. 10) and in 90 scenarios from 466 to 599.5 seconds (Fig. 11). 8 cases out of 90 scenarios has casualties and agents get stuck on the 8th floor of the building. ΔT is described as a comparison between the evacuation time of with fire snapshot and without fire snapshot (each snapshot is identical in comparisons). ΔT has three different categories, positive, negative and zero. As shown in Table. 4. the number of cases associated with each group of ΔTs are 38, 7, and 37 for ΔT>0, ΔT=0, and ΔT<0 respectively. The Table. 3 is showing the labels for each fire which is represented for better under understanding of Fig. 10 and Fig. 11.

Table 4. Fire labels

No.	Fire Location	Intensity	Label
1	Exit-Door-01	High	A1
2	Exit-Door-01	Low	A2
3	Exit-Door-02	High	H1
4	Exit-Door-02	Low	H2
5	Exit-Door-03	Low	L
6	Exit-Door-04	Low	R
7	Spiral	High	Spiral

Table 3. Whole building - Number of snapshots

Whole Building-Number of Snapshots				
ΔT=0	ΔT>0	ΔT<0	Fatalities	Total
7	38	37	8	90

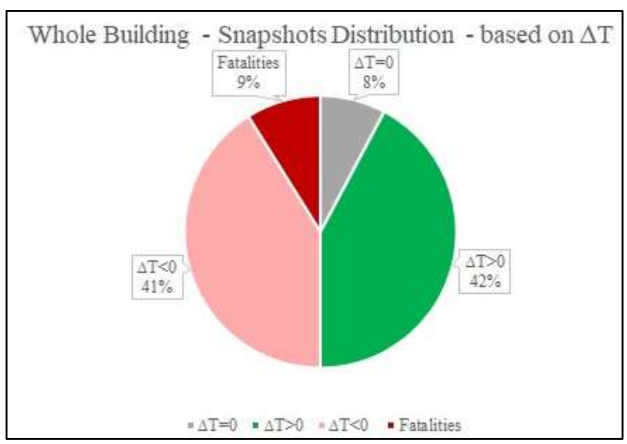


Figure 9. Whole building snapshots' distribution

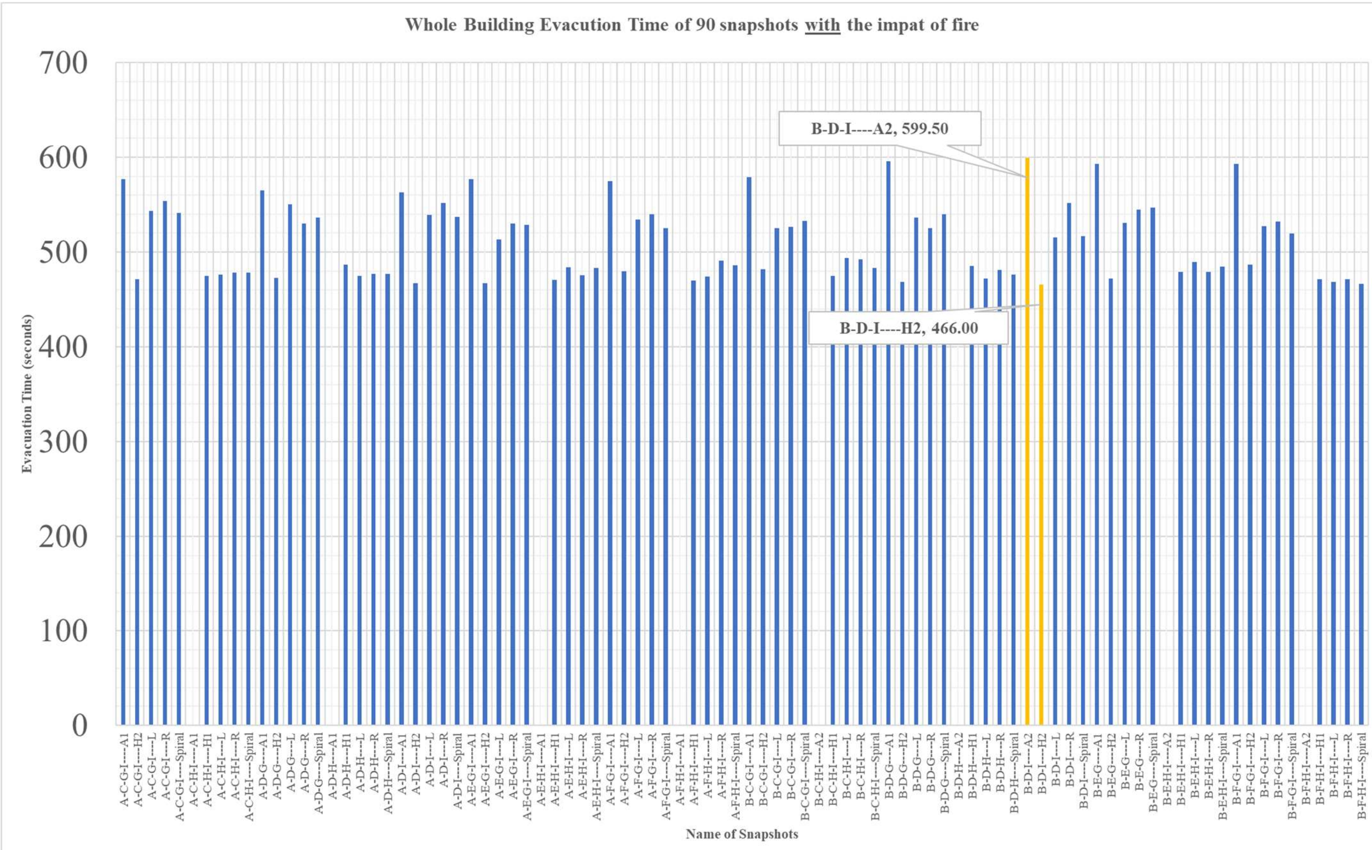


Figure 11. Whole building evacuation times for 90 snapshots with fire

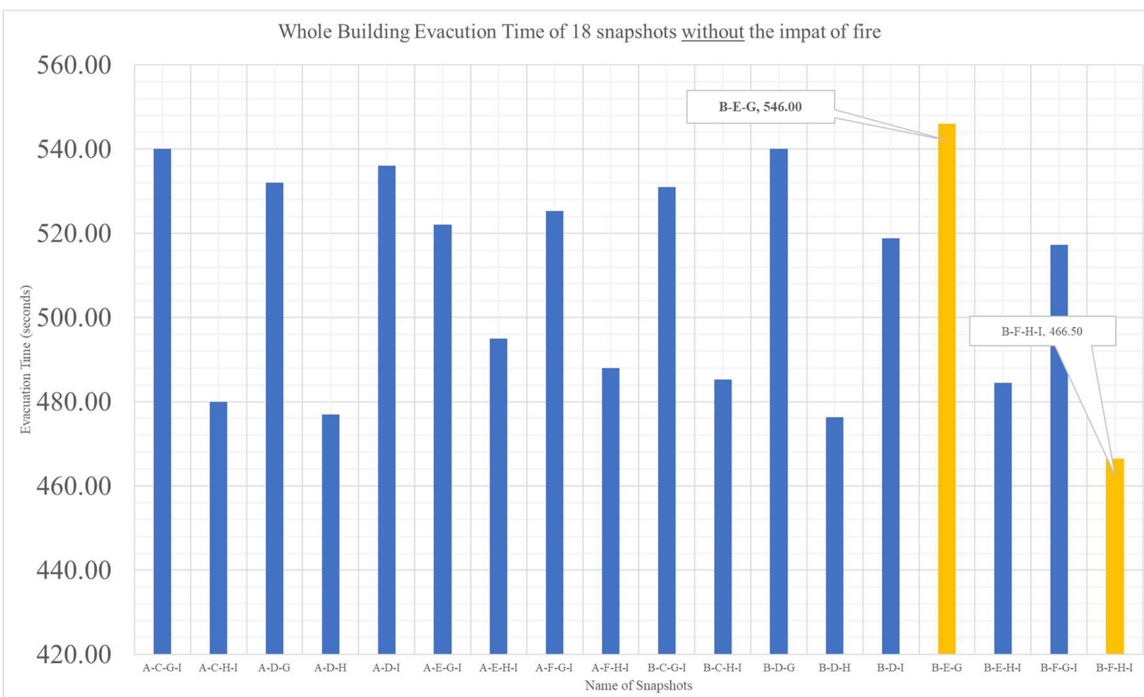


Figure 10. Whole building evacuation times for 90 snapshots without fire

5.1.2. 8th Floor Evacuation Result

The data driven from the 8th floor evacuation time shows that the egress times are distributed from 108 sec to 298 sec for 90 with fire snapshots (Fig. 14), and from 92 sec to 184 sec for 18 without fire snapshots (Fig. 13). Furthermore, results show that in 8 snapshots, the evacuation remained unfinished due to the blockage of only available exit door and people stuck in the floor. For the better illustration of the data associated with 82 remaining with-fire cases, a ΔT parameter is defined which is estimated from deduction of evacuation times of each with-fire from each without fire in the same snapshot. After this estimation, as it is illustrated in Fig. 12 and Table. 5, ΔTs are divided in 3 different group, ΔT>0, ΔT=0, ΔT<0. 50 out of 82 snapshots are in group ΔT>0, and from remained 40 cases, 20 of them are in ΔT=0 and the rest 12 are in ΔT<0.

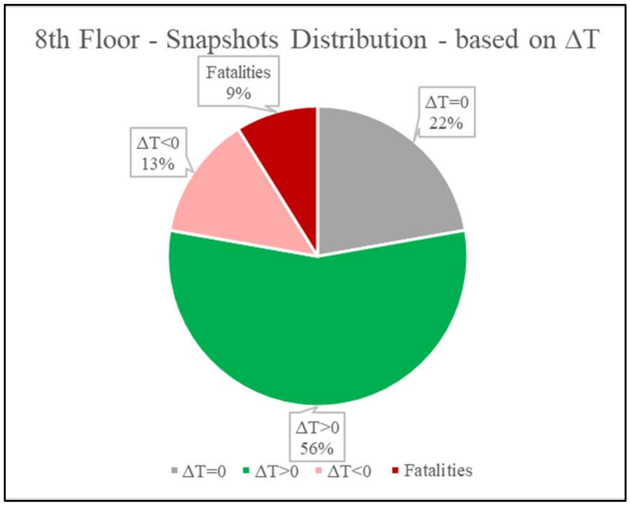


Figure 12. 8th floor snapshots' distribution

Table 5. 8th floor - Number of snapshots

8th Floor-Number of Snapshots				
ΔT=0	ΔT>0	ΔT<0	Fatalities	Total
50	20	12	8	90

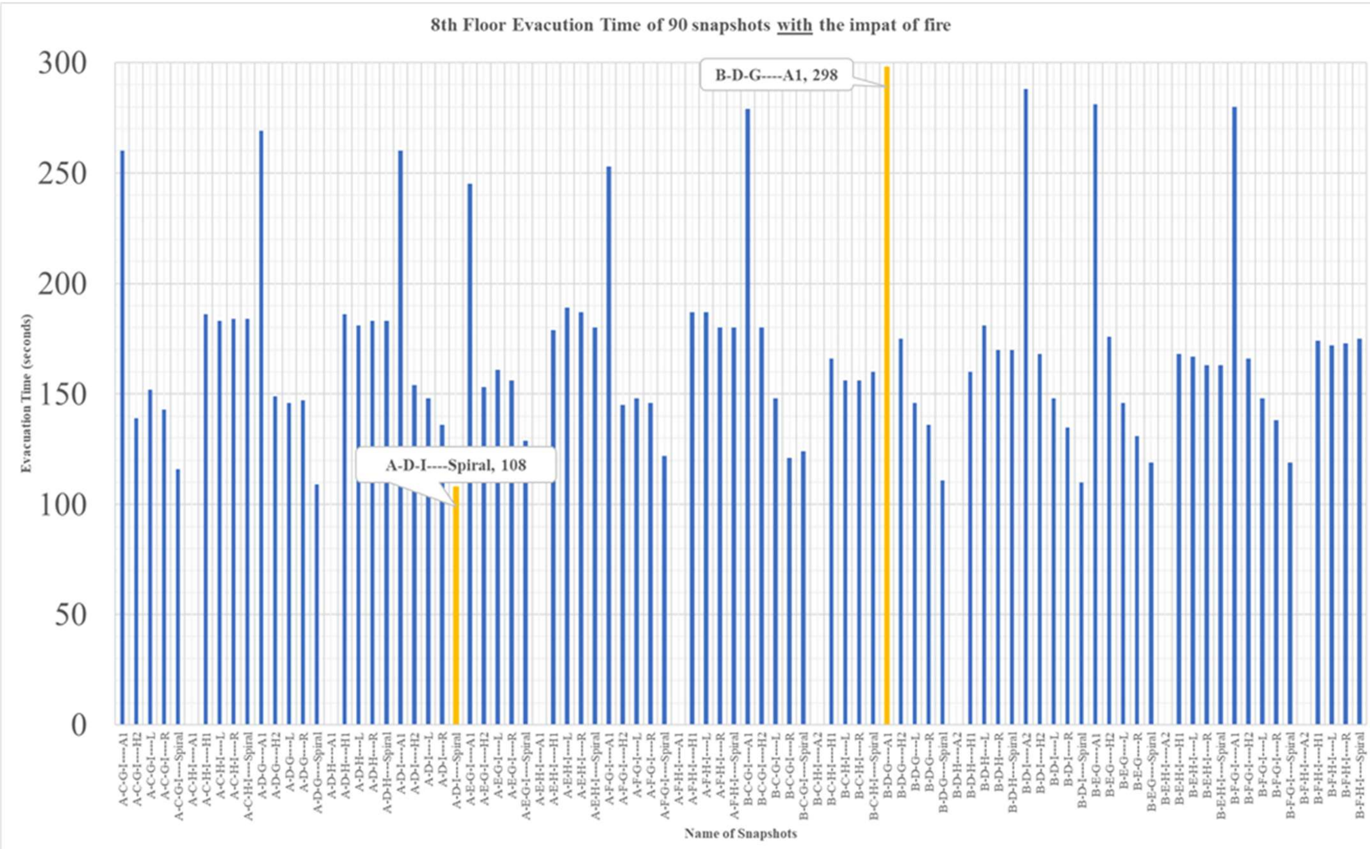


Figure 14. 8th floor evacuation times for 90 snapshots with fire

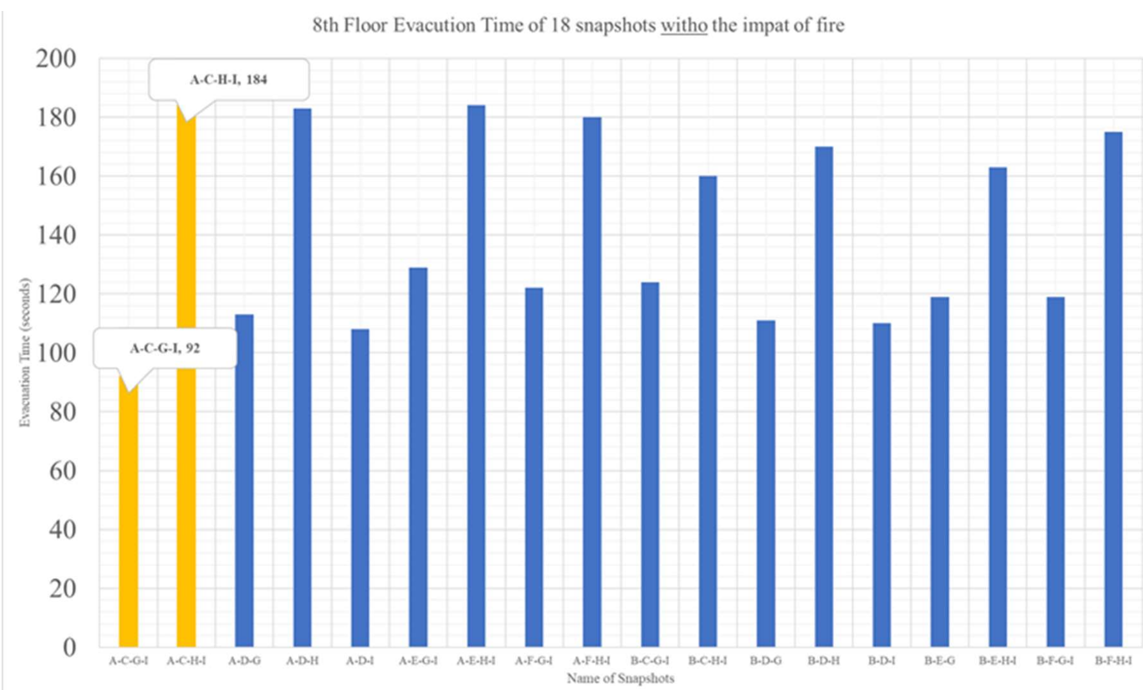


Figure 13. 8th floor evacuation times for 90 snapshots without fire

5.2. Analysis and Discussion

In this section the ΔT is used for the purpose of comparison between with and without fire snapshots. ΔT is defined based on the deduction of without fire evacuation time ($RSET_{Without\ Fire}$) from with fire one ($RSET_{With\ Fire}$). As is explained by Shams Abadi [6], the higher value of ΔT, represents the higher risk associated with a case.

5.2.1. 8th Floor Evacuation

5.2.1.1. Slower Evacuation Cases

In this category of results that includes almost 60% of all 90 with fire snapshots' results, the evacuation time of the 8th floor in with fire condition is higher than without fire ones and they are represented by $\Delta T>0$. The one of main reasons that causes this more evacuation time in with fire cases is the reduction in visibility range and speed of occupants due to the smoke based on the technical support of Pathfinder software tool which in detail is explained in Shams Abadi's [6] report [15]. This longer evacuation time approves the hypothesis of more required time for evacuation in the presence of fire. As assumed the evacuation time of without fire snapshots is safe, so any longer evacuation time compared to without fire case is considered as risky. The variation of differences (ΔT) is from +2 to +187 and the larger number in ΔT represents the higher risk associated with that specific snapshot (Fig. 15).

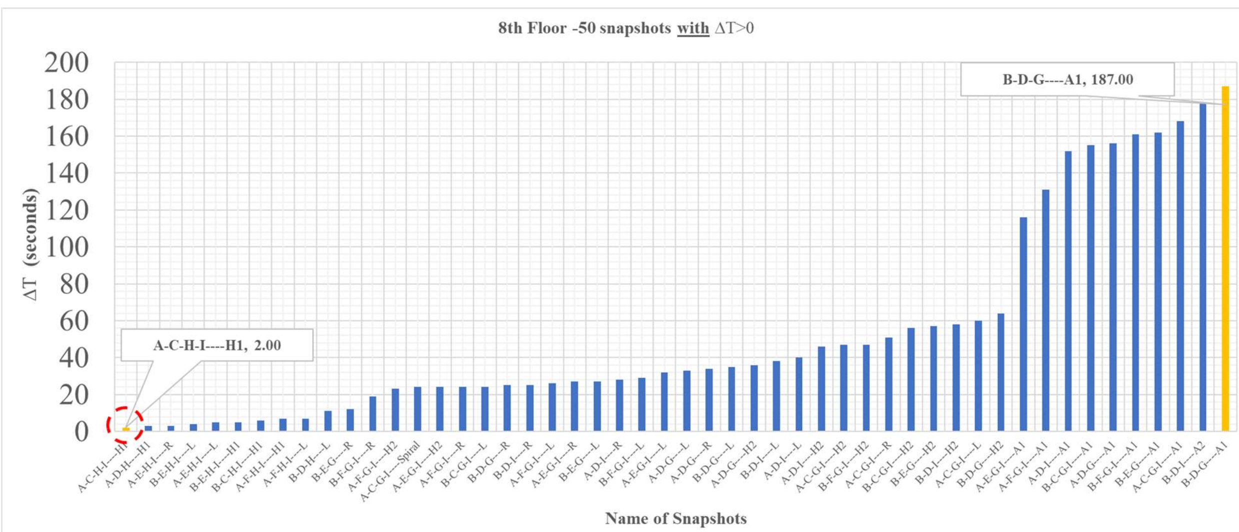


Figure 15. 8th floor-50 snapshots with ΔT>0

5.2.1.2. Faster Evacuation Cases (Anomaly case)

This category of results, with a negative value of ΔT, represents the faster evacuation of occupants in with-fire snapshot compared to without-fire one that rejects the hypothesis of more required egress time for occupants in presence of fire. Based on the proposed concept, this category is considered as an anomaly. In the Table. 6, 12 anomaly cases with $\Delta T<0$ are listed and the associated ΔT with these cases are shown from -1 second to -10 second.

Table 6. 12 anomaly cases with ΔT>0

No.	Snapshot	Fire Location	Intensity	ΔT
1	A-E-H-I	Exit Door-2	High	-5.00
2	B-D-H	Exit Door-2	High	-10.00
3	B-F-H-I	Exit Door-2	High	-1.00
4	A-C-H-I	Exit Door-3	Low	-1.00
5	A-D-H	Exit Door-3	Low	-2.00
6	B-C-H-I	Exit Door-3	Low	-4.00
7	B-F-H-I	Exit Door-3	Low	-3.00
8	B-C-G-I	Exit Door-4	Low	-3.00
9	B-C-H-I	Exit Door-4	Low	-4.00
10	B-F-H-I	Exit Door-4	Low	-2.00
11	A-D-G	Spiral stair	High	-4.00
12	A-E-H-I	Spiral stair	High	-4.00

Among these cases, the B-D-H snapshot with high intensity fire in front of exit door 2 and ΔT of -10 second, has the fastest evacuation time and it is selected for investigation on the possible reason behind this specific category of anomalies.

The case B-D-H, as it is shown in the Fig. 16, has 3 construction sites, two in the labs B and D, and one in the corridor which is named by "H" letter. According to the preliminary assumptions of Construction Planning report in section Renovation Type and Location [6], construction site is only accessible to the associated crew with each site and occupants can not go through these spaces. Therefore, in the all cases with H-part, there is no connection between V-part and E-part of the floor. Additionally, Exit Door-02 which is in the H-part is considered closed for both the occupants and the crew. Thus, the only available exit door for people in the V-part is Exit Door-01.

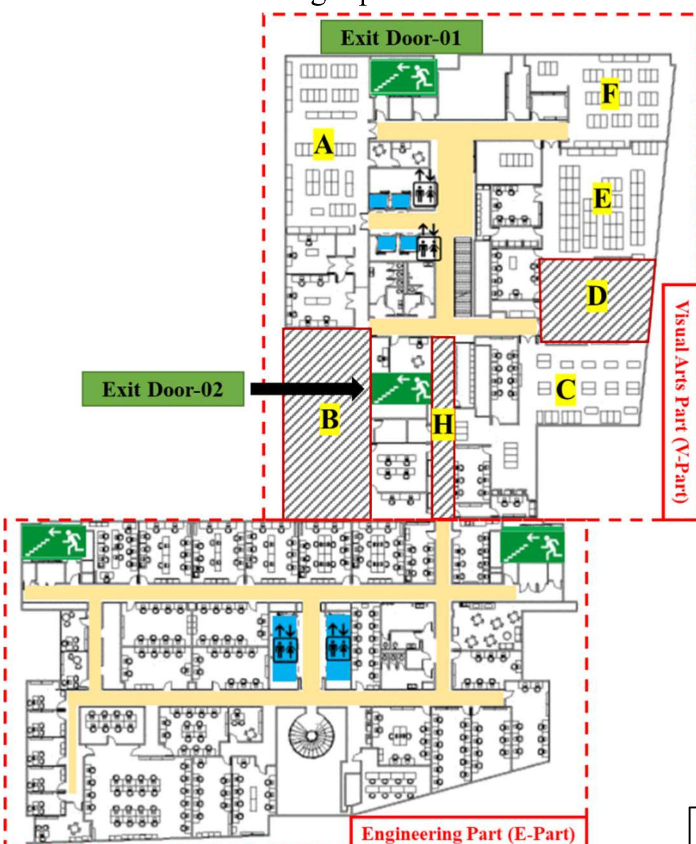


Figure 16. B-D-H construction snapshot

Extracted data of exit doors' evacuation times from the simulation results (Table. 7) shows that Exit Door-01 has the longest evacuation compared to other exit doors in the 8th floor with evacuation time of 160 sec. In this specific case, Exit Door-01 is the critical door and controls the evacuation time of the entire 8th floor.

Table 7. Evacuation time of exit doors in B-D-H snapshot

Evacuation Time for Each Exit Door (sec)			
Exit Door-01	Exit Door-02	Exit Door-03	Exit Door-04
160	0	50	38

The calculated number of occupants by Shams Abadi [6] shows that V-Part has 119 agents and E-Part has 57 agents. The available doors for evacuation of occupants in E-Part are Exit Door-03 and Exit Door-04, and in V-Part is only Exit Door-01. Therefore, it is obvious that 119 people in V-Part require more time to evacuate through one door compared to 57 agents in E-Part with two available egress doors. According to the mentioned information above, the investigation process of B-D-H is narrowed down into the only V-Part due the proposed criticality of Exit Door-01 and disconnection of V-Part from the E-part [6].

Based on the detailed evacuation result associated with each agent, the last evacuated agents in with-fire and without fire simulation of B-D-H are extracted. It is observed that, agents 99 and 60 with evacuation time of 160 and 170 seconds are the last ones in the egress process in with-fire and without fire respectively. As illustrated in Fig. 17, agent 99 is located in lab F (close to Exit Door-01) and agent 60 is in the bottom part of lab C (far from Exit Door-01). Based on required distance of these agents to exit, it was expected that the agent 60 with longer distance from exit door, evacuates later than agent 99 in with-fire but she evacuated in 133 seconds and faster than agent 99.

Through watching the evacuation simulation video, the time when agent 60 reaches to the congestion in both with and without fire cases are extracted. In both cases, she reached to the queue at 57 seconds after the beginning of her evacuation although her first location in the congestion is different in with and without fire scenarios. Additionally, as shown in the Table. 8, simulation videos show that the order of other agents either in the congestion is different in with and without fire scenarios. Another observation in the agent 60 speed variation is that she has same speed in with and without fire from 0 sec to about 57 sec which is the time she reaches into the congestion. From 57 sec till the end of her evacuation, she starts moving with different speeds in with and without fire cases (Fig. 18). Thus, the only possible difference between these two cases might be the movement flow of the congestion impacted by smoke. Because the only difference between with and without fire model is the fire and everything is identical.

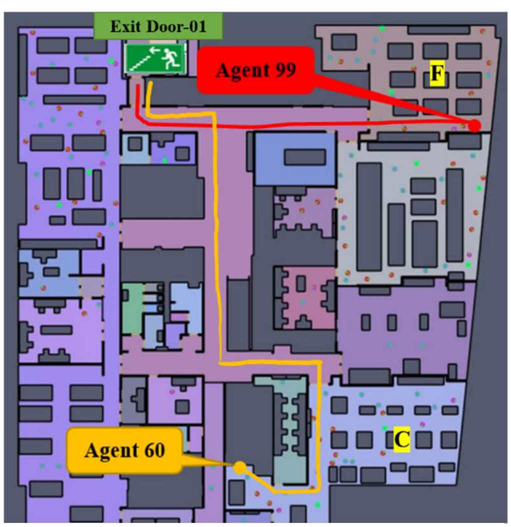


Figure 17. Agents 60 and 99 locations in the floor

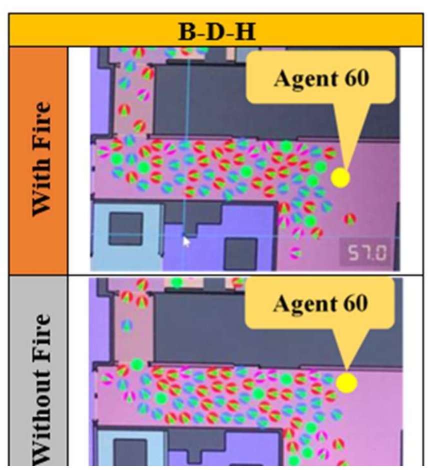


Table 8. Order of agents in the congestion

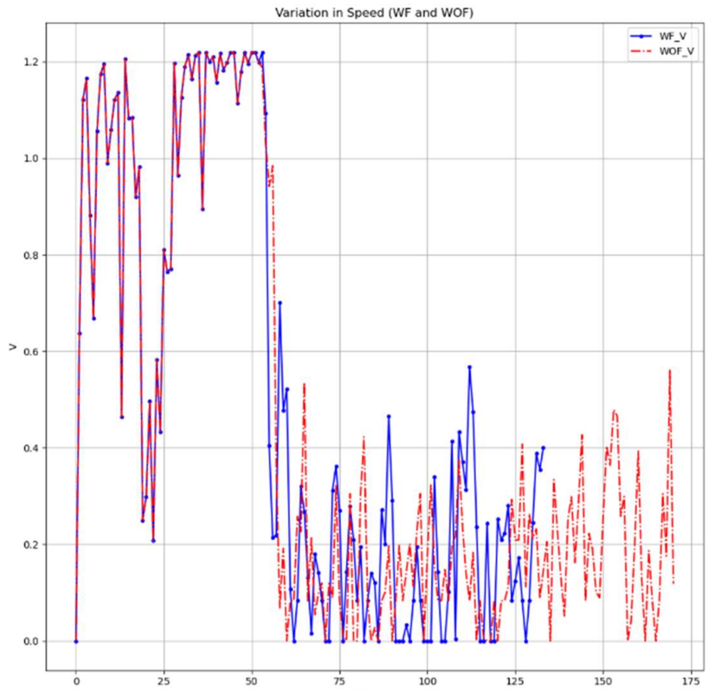


Figure 18. Agent 60 speed comparison in with and without fire

In addition, the results of smoke propagation are extracted from the defined visibility slice in the Pyrosim and are shown in Fig. 19. This slice is located at 1.8 meters from the floor level which is chosen based on the assumed height of the agents in the evacuation modeling. In Fig. 19, smoke propagation for 4 different time steps are illustrated. In all captured pictures there is a rectangular metric on the left-hand side of each picture. This metric shows the colors from red to dark blue. Red color means the horizontal visibility is 3m and dark blue means the visibility is zero. With respect to these definitions, at the time step 35 seconds, almost in the entire V-Part, visibility is still in the max value (3m) at the height of 1.8 m although in 4 spots the visibility range decreased to roughly 1.5 m. After 5 seconds, at the time step 40, the loss of visibility started appearing in front of Exit Door-01 but it is not considerable yet. At the time step 57 which is the time agent 60 reaches into the congestion, the entire corridor in front of the Exit Door-01 covered by smoke and the visibility in most locations is close to zero and all the occupants in the congestion are exposed to the smoke.

The information about evacuation time of agent 60 and fire propagation show that as a hypothesis, by the time people are evacuating and getting into the congestion, there is yet no smoke because the source of fire is far from the Exit Door-01 or the intensity of that is not adequate. So, the with and without fire evacuation are almost the same during this period, with only small difference in the number of people in the congestion (with fire case has 2 agents more than without fire one in the congestion at the time step 57 seconds). But when the smoke completely reaches to the congestion at the time step 57 seconds, it might help the congestion to move smoother and lets occupants evacuate faster. However, this hypothesis requires more investigation to be justified.

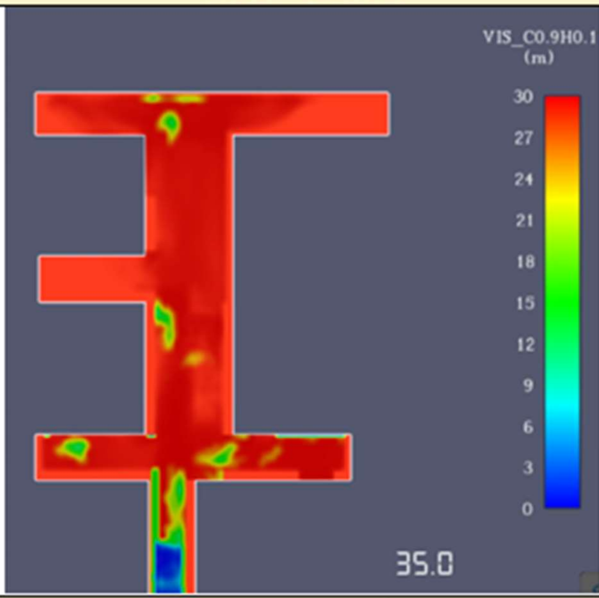
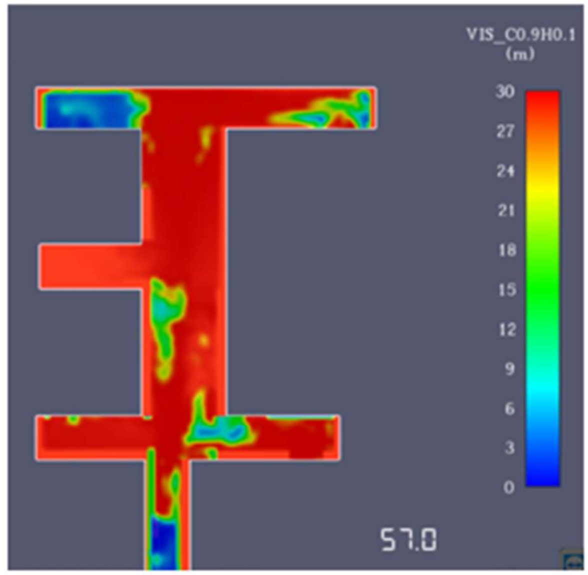
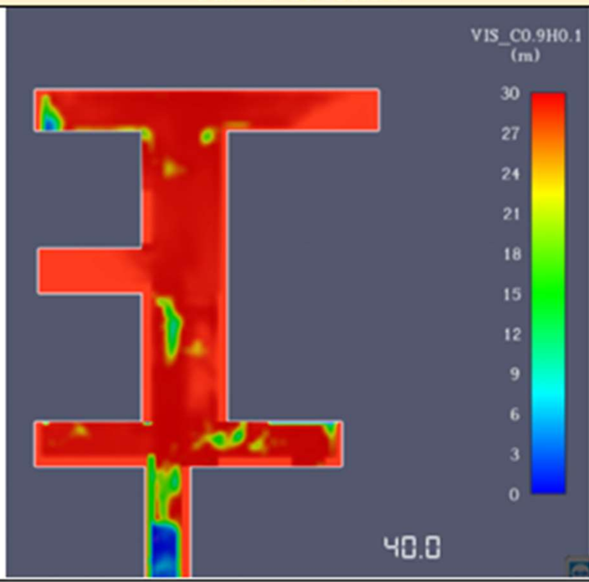
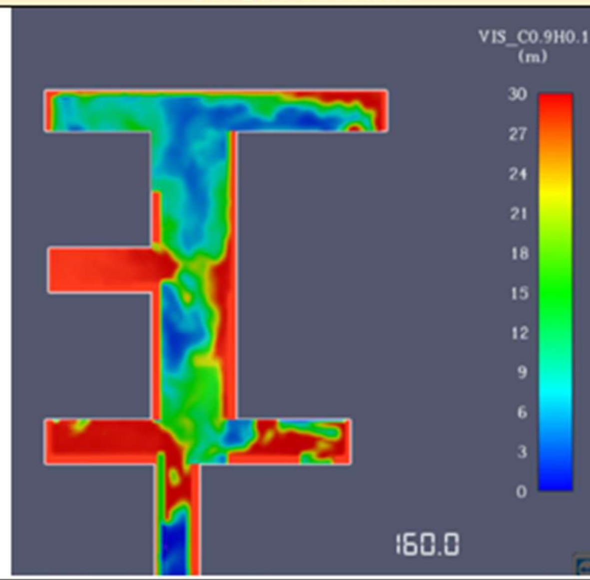
Visibility Slice at 1.8 m from the floor level – Smoke propagation in different times of simulation	
At 35 seconds	At 57 seconds
	
At 40 seconds	At 160 seconds
	

Figure 19. Visibility slices results - 1.8 m height-Fire in front of Exit Door-02, High Intensity

5.2.1.3. Not Impacted Cases (Anomaly case)

From the total 90 with fire snapshots, 20 of them have the same evacuation time in with fire case compared to without fire one which rejects the hypothesis of longer evacuation in the presence of fire and they are also considered as anomaly for the investigation.

These 20 cases with $\Delta T=0$, based on the presence of construction site in each associated snapshot, are divided into two groups; 1) having closure at H-Part due to the renovation, 2) having open corridor at H-Part. When H-Part closes the corridor, the connection between E-Part and V-Part is cut off. Hence the Exit Door-02 is also closed, the only available exit way for people in the V-Part is Exit Door-01. Based on the occupant's distribution calculation mentioned in Shams Abadi's [6] report, the majority of the occupants are located in the V-Part and they need more time to evacuate through the only available door. Thus, this door is critical and controls the evacuation time of entire floor in 12 cases of the group number one with H-Part closure.

In another group, there is no corridor renovation at H-Part in the associated snapshots. So, the Exit Door-02 is available for the occupants' evacuation and E-Part is accessible through V-Part. In the 8 remaining cases in group number two, when all the exit doors are available for egress process, Exit Door-02 is the critical one due the shorter width of its staircase (1.8m) compared to other 3 staircases' width (2.4m). In the case of shorter staircase's width, the process of evacuation requires more time to be completed.

In the cases that Exit Door-01 is critical, fire is in front of spiral stair or in front of Exit Door-04 and both fire locations are in the E-Part. Furthermore, in all the remaining cases that Exit Door-02 is critical, fire is always located in front of spiral stair. Thus, as illustrated in Fig.20 and Fig.21, in both type of cases, fire is far from the occupants in the congestion.

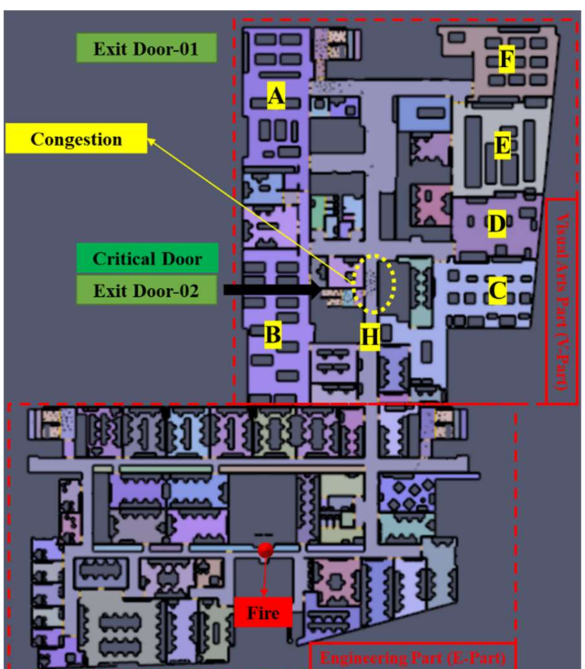


Figure 21. A-D-I construction snapshot with high intensity fire in front of spiral stair

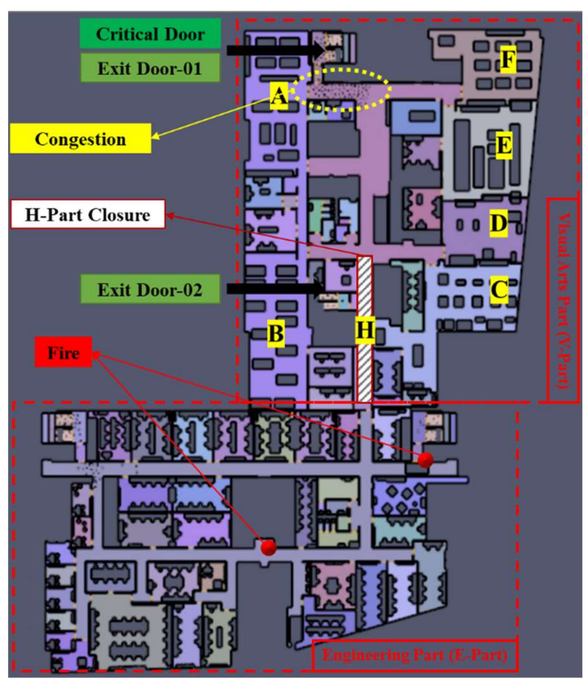


Figure 20. B-D-H construction snapshot with high intensity fire in front of spiral stair and Exit Door-02

According to the fire slices' results (Fig. 23 and Fig.24), propagation of smoke shows that in both fires, during all the evacuation process of occupants, fire does not reach to the congestion and does not impact them. Based on the data driven from co-simulation in Shams Abadi's [6] report , associated evacuation time and speed of each occupant in V-Part of B-D-H snapshots in both with and without fire are compared. The result of comparison shows that, in this case which is selected among the 20 cases of this category, the accumulated speed of 119 agents which are in the V-Part, in each time step is exactly the same in with and without fire snapshots of B-D-H (Fig.22).

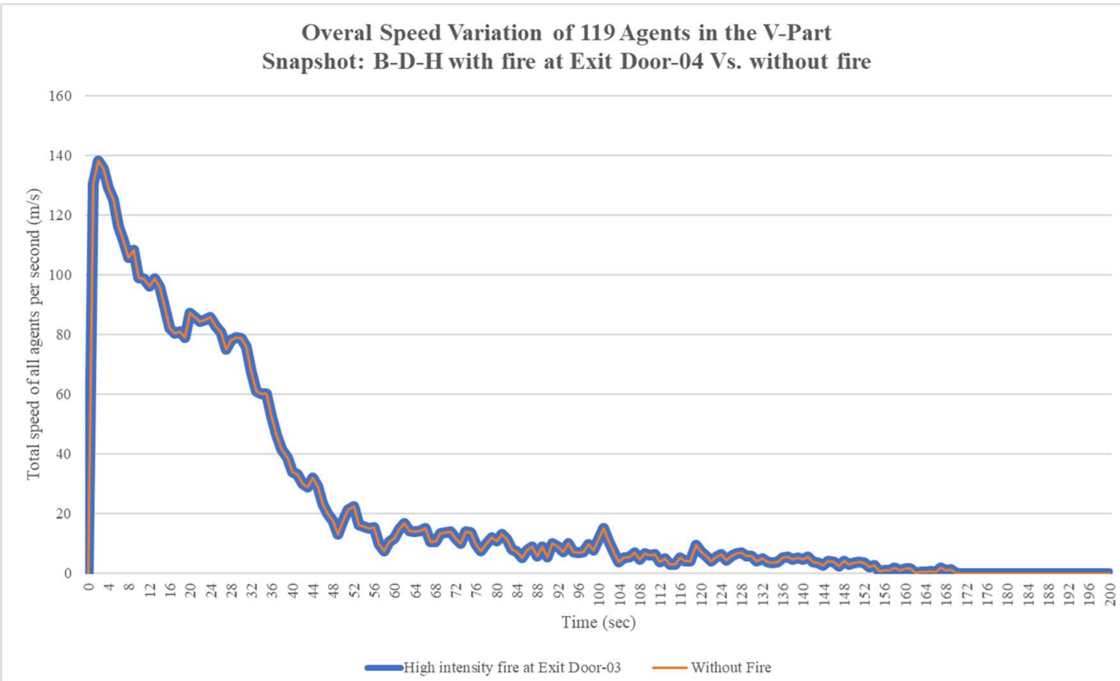


Figure 22. Overall speed variation of 119 agents in the V-Part

Therefore, the reason behind same evacuation times for with and without fire cases in this category is that evacuees are not impacted by fire which is far from the congestion and the evacuation time is dependent to the critical exit door.

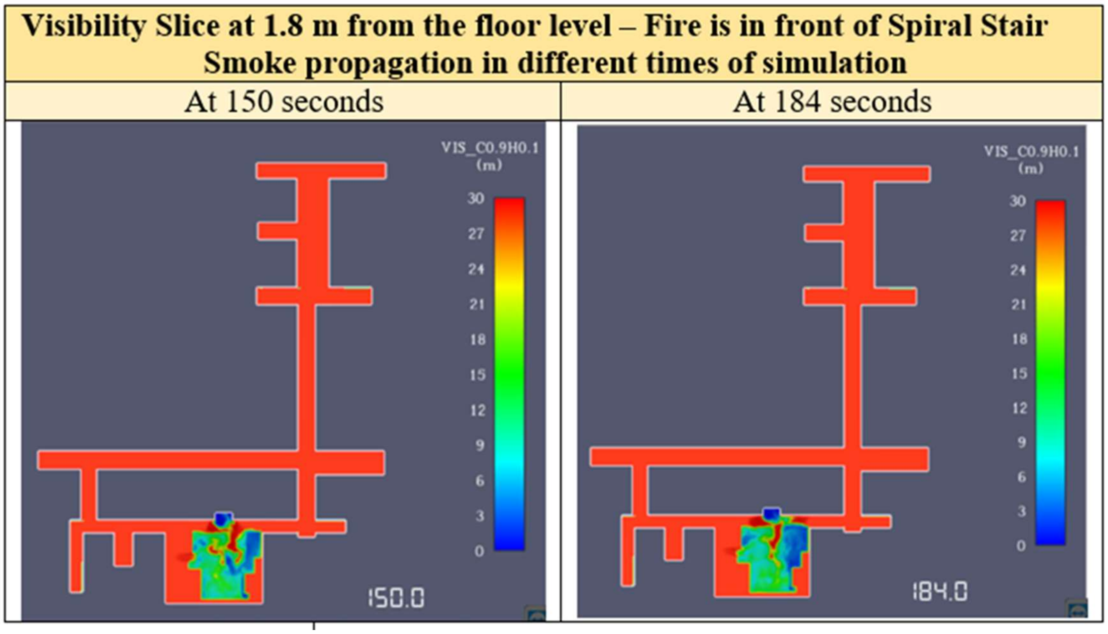


Figure 24. Visibility slices results - 1.8 m height-Fire in front of spiral stair, High Intensity

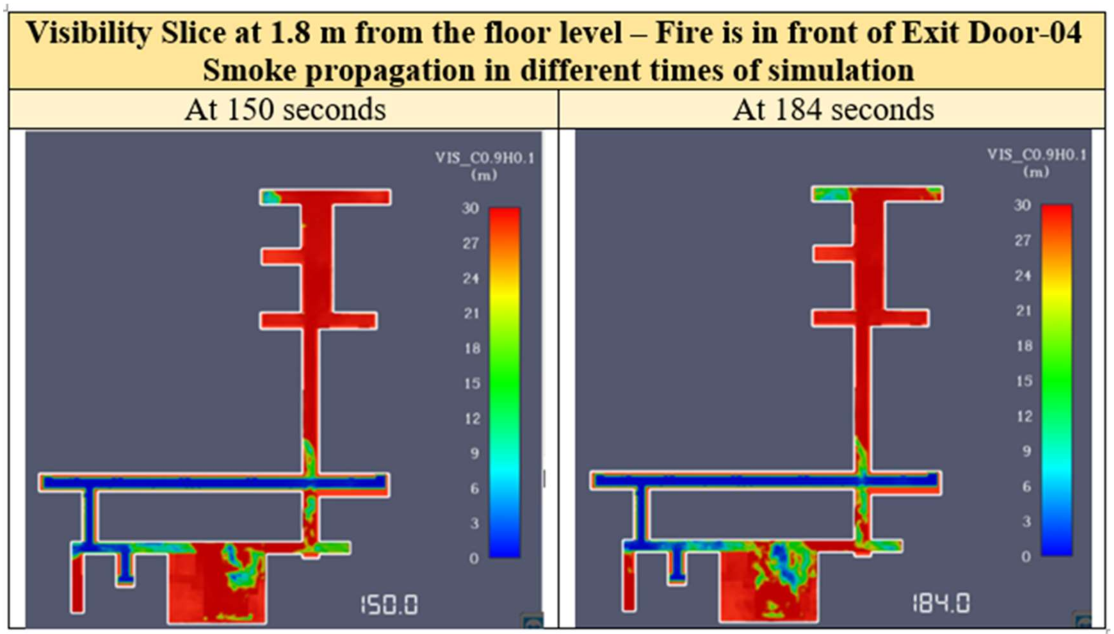


Figure 23. Visibility slices results - 1.8 m height-Fire in front of Exit Door-04, Low Intensity

5.2.2. Whole Building Analysis

5.2.2.1. Slower Evacuation Cases

In slower evacuation cases, ΔT is positive. The scenario with fire has more evacuation time compared to the same scenario without fire. Among 90 scenarios including fire the number of slower evacuation cases are 38 which is 42% of the total snapshots (Fig. 9). The ΔT in these cases varies from 0.5 to 80.7 seconds. The total slower evacuation cases are illustrated in Fig.25. The without fire scenario evacuation times, are considered as the safe baseline for each snapshot, closer evacuation times to the baseline are safer in the matter of evacuation, so higher ΔTs have less safety in terms of evacuations.

Based on the technical reference of the Pathfinder, it is expected that, by implementing the fire, the visibility of the agents reduces and the speed factor of smoke, mentioned in Shams Abadi's report, would be applied on the original speed of the agents. As a result, the agents exposing to the smoke have slower evacuation and the whole evacuation time is increased. [21]

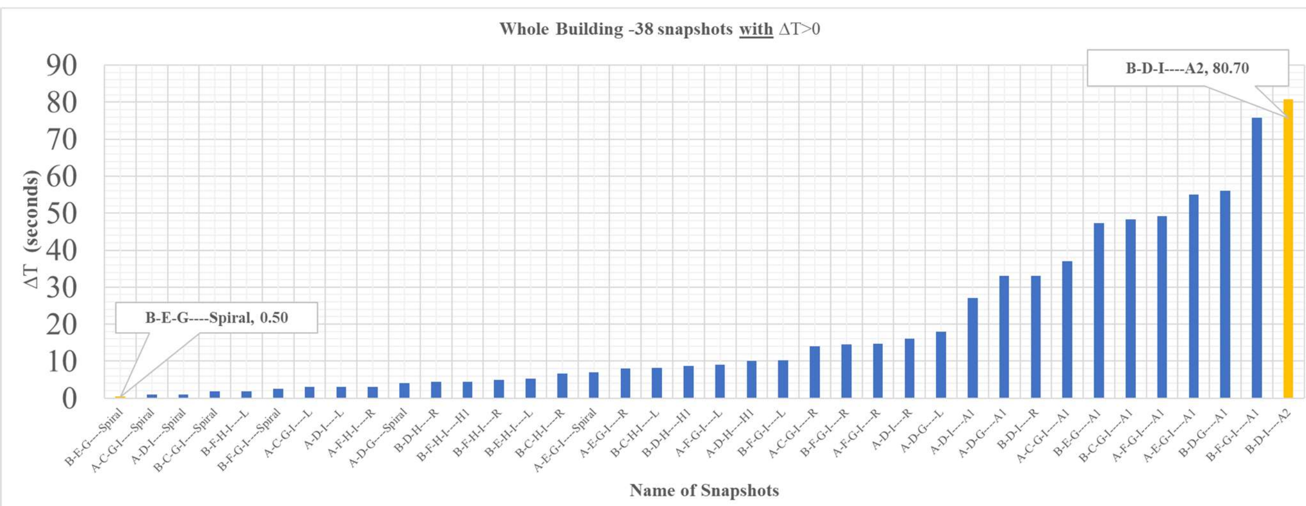


Figure 25. Whole building-38 snapshots with ΔT>0

5.2.2.2. Faster Evacuation Cases (Anomaly Case)

ΔT with negative value is the representative of cases in which the with fire snapshot evacuation time is less than without fire snapshot evacuation time. It means by implementing the fire, the evacuation time become less than the base model (without fire). The faster evacuation cases are 41% of all the snapshots (Fig.9). The ΔT values in these cases varies from -1 to -73.7 seconds. All the whole building's cases related to this category and their associated ΔTs are illustrated in Fig. 26. It is expected that by applying the fire, the evacuation time in with fire snapshot becomes greater than without fire one and agents be slowed down. For investigating the reason of this anomaly, the critical staircase should be analyzed. The critical staircase is the one that determines the total evacuation time of the whole building, which the last occupant in the building is evacuated from that. By analyzing all the anomaly cases of this category, it is found that in all of them, the critical staircase is Staircase-02 (locations of all staircases are shown in Fig.27) and the reason is a narrower width compared to other staircases. The rest of three safe pressurized staircases have 1.8-meter width (Fig. 29), and the staircase-02 has 1.1-meter width (Fig.28). This difference in the width make this staircase critical and provides more congestion and load on that.

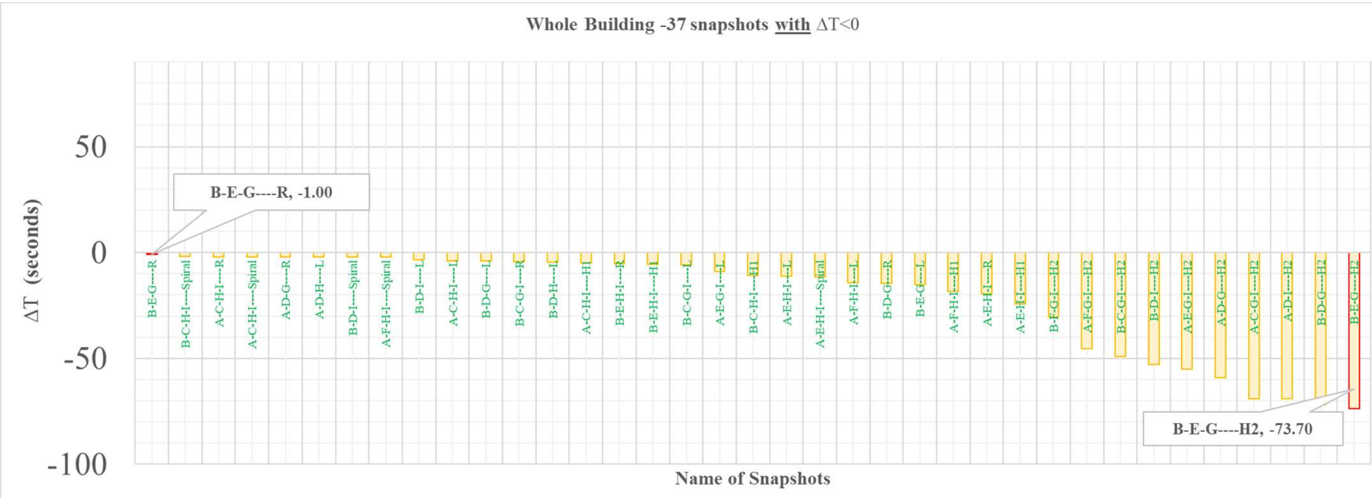


Figure 26. Whole building- 37 snapshots with $\Delta T<0$

Figure 27. Staircases' locations

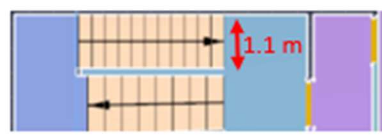


Figure 28. Staircase-02 width

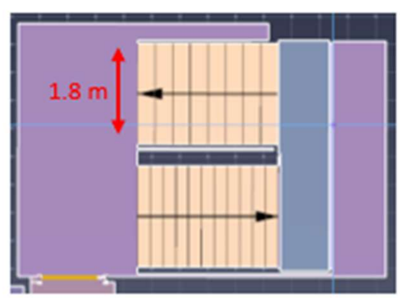


Figure 29. Staircase-01, 03, 04 width

To analyze this anomaly, one sample, B-E-G snapshot with closure at H-Part and fire in front of Exit Door-02 is investigated as a representative of this group of anomalies. First, the density of each exit door in each floor is extracted to calculate the associated staircase load. The Table. 9 illustrates the load added or deducted from Staircase-02. It is calculated by the comparison between the density of each door in with fire case and without fire case. Two scenarios are illustrated in Table. 10. The Fig.30 shows the changes in the density of the Staircase-02 by implementing the fire. Fire not only has impact on agents' behavior in 8th floor, but also has impact on the agents in 10th floor and 11th floor.

Table 9. Added or Deducted load to Staircase-02 in 16 floors

Floor	B-E-G Exit Door-02 Density With fire	B-E-G Exit Door-02 Density Without Fire
1	19	19
2	19	19
3	19	19
4	18	18
5	18	18
6	18	18
7	16	16
8	0	48
9	50	50
10	50	59
11	31	42
12	15	15
13	15	15
14	15	15
15	14	14
16	14	14

Table 10. Added or Deducted load to each staircase in 16 floors

Floor	Deducted or Added Load Staircase-01	Staircase-02	Staircase-03	Staircase-04
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	45	-48	0	3
9	0	0	0	0
10	-9	-9	0	0
11	0	-11	0	-11
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
	36	-68	0	-8

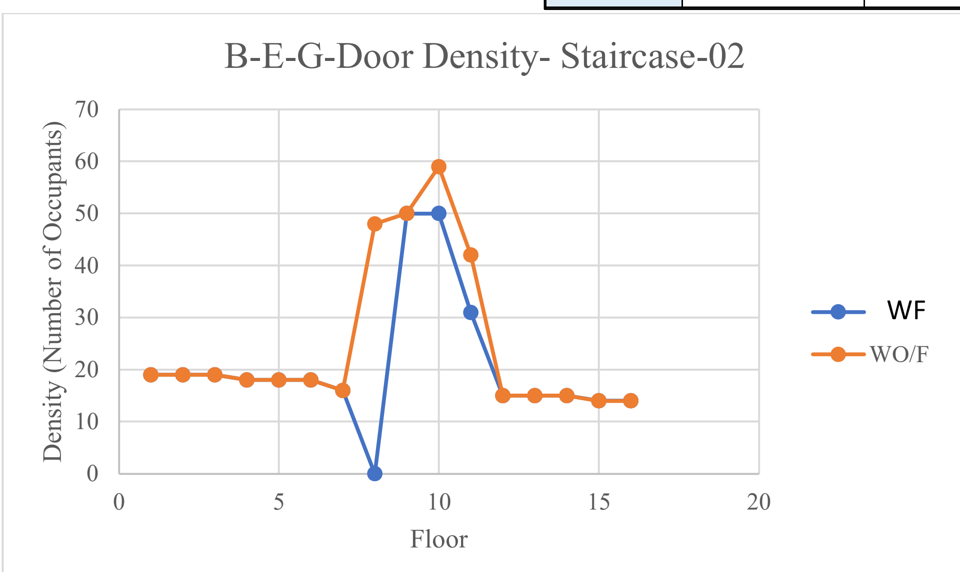


Figure 30. Variation in Staircase-02 density in with and without fire of B-E-G

The load of critical staircase is decreased and accordingly, the time of evacuation from that staircase is decreased. Staircase-02 is always critical, the evacuation time of the whole building is decreased.

In all the cases with fire in front of the Exit Door-02 while no construction is in H part, the evacuation time of the whole building is decreased after implementing the fire. The reason is reducing the load of critical staircase by having a fire in front of that.

5.2.2.3. Not Impacted Cases (Anomaly Case)

Not impacted cases are scenarios that implementing fire in them does not have any impact on the evacuation time of the snapshot and the evacuation time of the with fire and without fire scenario is exactly the same, so that the ΔT is zero. The number of these cases are 7 from 90 scenarios. That is 8% of the total snapshots (Fig.9).

The reason of having no impact by implementing fire in scenarios, is investigated by considering the layout of the construction and the location of the fire. The scenarios including ΔT=0 are divided into two groups.

The first group is scenarios including ΔT=0 and H-part construction. H-part construction is the most critical construction renovation segment in this study. The reason is narrower corridor in this part and closing the whole corridor to respect the minimum available pathway in corridors. As a result of this closure, Exit-Door-02 is closed in with fire and without fire scenario, so by occurrence of the fire in front of Exit-Door-02 no load is exposed or deducted from or to Staircase-02. Staircase-02 is always the critical staircase due to the narrower width of opening which previously mentioned. The evacuation time of the whole building is determined by the critical staircase and in scenarios including ΔT=0 and H-part construction, the density and time of the agents evacuating from Staircase-02 is not changed due to the closure of Exit-Door-02.

In Table. 11 the A-D-H base including density and time of the evacuation from each staircase is illustrated. Same information is presented in Table. 12 for the A-D-H with fire in front of Exit Door-04 and low intensity. The critical staircase in both cases is Staircase-02 and the density and the time is steady. However other staircases have some changes in the number of agents and the time, the evacuation time of the whole building is not determined by their time because they are not critical.

Table 11. A-D-H without fire exit doors' density

A-D-H (Without Fire)				
	Exit Door-01	Exit Door-02	Exit Door-03	Exit Door-04
Density	381	304	300	179
Time (sec)	465	477	340	273

Table 12. A-D-H with fire exit doors' density

A-D-H (With Fire)				
	Exit Door-01	Exit Door-02	Exit Door-03	Exit Door-04
Density	381	304	322	157
Time (sec)	465	477	359	338

In the second group, there is no construction in H part and the fire is in front of spiral staircase. As mentioned in the discussion of 8th floor not impacted cases, in this group fire is far from the critical door and the smoke does not have impact on the evacuation time and density of the critical door. An example of this case, B-D-G with fire in front of spiral stair and high intensity, is presented in Table.13 and Table. 14.

Table 13. B-D-G without fire exit doors' density

B-D-G (Without Fire)				
	Exit Door-01	Exit Door-02	Exit Door-03	Exit Door-04
Density	341	343	300	180
Time (sec)	419	540	340	363

Table 14. B-D-G with fire exit doors' density

B-D-G (With Fire)				
	Exit Door-01	Exit Door-02	Exit Door-03	Exit Door-04
Density	341	343	300	180
Time (sec)	419	540	340	363

In this case (B-D-G with fire in front of spiral stair) smoke has only impact on the staircase-04. This staircase is not critical and does not have impact on the evacuation time of the building.

6. Conclusion, Limitations, and Future Works

This study by proposing a fire and evacuation framework investigated the impact of fire on occupants' evacuation in a building under construction renovation. Through this framework with respect to the received information from the construction planning and building properties, fire scenarios were generated. Then, with utilization of BIM environment, fire and evacuation were modeled. After modeling, by running the Co-Simulation, the results were obtained. By analyzing the co-simulation results, it was verified that the presence of fire in renovation work increased the evacuation time in 60% of cases in 8^{th} floor and about 40% of cases in whole building which showed the higher potential of injuries and casualties. However, in the rest of the remaining results it was observed that the evacuation time in with fire cases compared to without fire stayed the same or decreased which were considered as anomaly cases.

In the investigation of the anomaly cases, some hypotheses were proposed but for justification of them more investigation is required. Because of the complexity of Agent Based Modeling and large number of cases under investigation of this study.

By analyzing the results, it was found that in the multiple cases with H-Part closure in the middle of floor, the floor was divided into 2 halves. In the one half only one exit door was available for evacuation. When fire was considered in front of only available exit door, the occupants stuck and probably they were died. Therefore, construction planner should be mindful that always consider the minimum of 2 available exit doors for each occupant. Also, construction planner should be mindful that the capacity of critical exit doors and staircases at the stage of planning should be identified for distributing the occupants evenly between all exit doors and staircases and achieving a safe evacuation.

Among selected fire locations, the fire in front of the spiral stair, had the least impact on evacuation due to the chimney effect. In the generation of fire scenarios, instead of selecting fire in 5 locations, other possible locations and also multiple fires at the same time should be modeled and tested. In the fire modeling simulation, it is highly recommended to assign multiple meshes to different available cores of processor for decreasing the analysis time. The fire model in this study is still simple and can improve in future studies by defining advanced fire properties, adding more devices such as sprinkler and HVAC system, and modeling entire floor's spaces instead of only the corridors. Additionally, although in this study fire propagation based on materials is not modeled due to the huge volume of analysis time, the impact of this propagation will be investigated as the future works.

The entire building's Revit model of the case study was created based on the 9^{th} floor model which might affect the fire and evacuation modeling and simulation results.

In the process of co-simulation, Pathfinder only considers the reduction in visibility due to smoke, but other important factors such as CO concentration, FED level, and temperature also should be considered.

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